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Design and Manufacturing Final Report for Alternate Fixed Distributed Systems (FDS) Deep Water Trunk Cable, Phases I and II

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NAVAL COMMAND, CONTROL AND OCEAN SURVEILLANCE CENTER
RDT&E DIVISION
San Diego, California 92152–5001

H. A. WILLIAMS, CAPT, USN
Commanding Officer

R. C. KOLB
Executive Director

ADMINISTRATIVE INFORMATION

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Released by
T. N. Roy, Acting Head
Advanced Applications
Branch

Under authority of
J. E. Watring, Head
Acoustic Systems and
Technology Division

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1.0 INTRODUCTION

This report covers the design and manufacturing of Alternate Deep Water Trunk Cable (ADWT), which is being developed by Naval Ocean Systems Center (NOSC), Advanced Applications Branch-Code 714, for the Fixed Distributed Systems (FDS) Program Office-PMW 184, U.S. Navy Space and Warfare Command (SPAWAR). The work was performed during the period beginning 01 April 1989 and ending on 14 June 1990.

The goals of this development program were to reduce design and manufacturing risks, and if possible, to:

* Reduce production costs;
* Increase availability and competition by qualifying multiple vendors employing standard machinery;
* Increase production rate;
* Increase product quality;
* Improve cable performance;
* Eliminate the requirement for high-technology manufacturing processes.

In achieving these goals, the program would take advantage of lessons learned by the Navy in developing the Center-Strength-Member (CSM) cable.

The purpose of this report is to provide information both on the specific design variations pursued by the various cable suppliers, and to provide insight on the manufacturability of cable built in accordance with the proposed designs at the respective vendors' facilities. This is <u>not</u> a cable test report. Also, this document is <u>not</u> intended to provide a <u>detailed</u> economic cost analysis of cable productibility. However, in the course of providing cable design and manufacturing information, certain "preliminary" cable test results and/or materials cost data may be cited as appropriate to elaborate and underscore arguments related to cable design and productibility issues.

After digesting this report the reader should have a clear understanding of the particular designs manufactured by the respective cable vendors, how these designs relate to the corresponding manufacturing equipment available, and whether or not manufacturing problems occurred. Where manufacturing problems have occurred, the resolution of the problems are discussed. Furthermore, an evaluation is made of the specific vendors' capability to support volume production [$\geq$ 500 Nautical miles (Nmi)] of their particular cable approaches in the near future without facilitization and/or capital equipment investment. Explicit estimates are provided with respect to cost and time where a potential future vendor does **not** presently have the manufacturing capability for volume production, as for example, in the case of STC-Portland.

In order to make this report as self-contained as possible, the remainder of this Introduction provides background information on AT&T's FDS Deep Water Trunk (DWT) cable development in general, which leads in particular to a review of the strategy for development of the ADWT cable at NOSC. Also, Section 2.0 provides a summary review of the Phase I ADWT development at NOSC, which occurred between 04 May 1988 and April 1989. This explains the motivation for the Phase II cable designs discussed in Section 3.0. In Section 4.0 an analysis and evaluation of the various Phase II designs is given, along with an evaluation of the manufacturability issues. This leads to proposed changes for future procurement of Phase III cable having improved design and manufacturing characteristics. Finally, a summary of our conclusions and recommendations on ADWT cable design and manufacturing issues is contained in Section 5.0.

1.1 MOTIVATION FOR ALTERNATE CABLE DEVELOPMENT

The development of a small-diameter (0.372" OD) deep water trunk cable began as an AT&T Bell Labs (Whippany NJ) Internal Research and Development (IR&D) Project at Simplex Wire & Cable Co. (Portsmouth, NH) in 1981. This "miniature" deep water trunk cable was intended to be a scaled replica of AT&T's commercial Submarine Lightwave (SL) cable (0.872" OD), which was being developed at that time by Simplex for the Transatlantic Telephone No. 8 (TAT-8) Project. The first miniature prototype cable was designated as WI-01 (the "W" stands for Whippany). Subsequent developmental cables were designated as WI-02, WI-03, etc., where the number designation "03" can be considered not only as the third series of prototyping, but also can be roughly correlated with fiscal year 198<u>3</u>. For example, the eighth generation prototype cable, WI-08, was completed in FY88. The U.S. Navy funded the "small-diameter" DWT cable development by AT&T/Simplex from 1983 through 1990 (WI-03 through WI-09), to develop this cable for the FDS deep water trunk application.

During this long period of development, with its corresponding series of prototype generations, many problems were experienced in the manufacture and test of the cables. The cable diameter was increased successively from 0.372", to 0.450", and finally to 0.525"OD in attempts to meet performance and manufacturability requirements. These design and manufacturing problems, and the continual growth of the cable diameter, led to the establishment of the <u>alternate</u> DWT cable development at NOSC in April - May 1988. The **alternate** DWT design approach would attempt to circumvent the design, performance, and manufacturing problems experienced in AT&T's DWT cable development.

On 7 April 1988 AT&T presented a historical review of the DWT cable development to the FDS Program Office and contractor support team at TRW in McLean, VA. Several problems associated with past prototypes, including the (at that time) incomplete WI-08 fabrication were addressed. Several of the problems discussed at that time are shown in Table 1. This list provided the basis for the goals of the ADWT program.

On 15 April 1988 AT&T presented a higher-level management review to the FDS Program Office at SPAWAR, at which time they proposed to increase the diameter of the DWT cable to "somewhere between 0.500 and 0.625 inches OD" in order to improve cable manufacturability. Dr. Ken Hocker, the FDS Program Manager expressed concern that the cable cost would track the diameter increase, and within two weeks decided to set up a "risk management" **alternate** cable development program at NOSC.

TABLE 1. PROBLEMS DISCUSSED DURING HISTORICAL REVIEW, AT&T/SIMPLEX DEEP WATER TRUNK CABLE DEVELOPMENT (source: AT&T Presentation 7 April 88)

Prototype	**Problem**	**Resolution**
WI-03,-04, -05,-06	Insufficient Ruggedness	Cable diameter increase: 0.450" w/copper braid +outer HDPE Jacket
WI-06	Braid shield expensive	Change to phosphor bronze tube shield
WI-03 to WI-07	Fiber Buffer Difficult to Manufacture	AT&T/Atlanta vs Simplex provide fiber buffer
WI-03 to WI-08	Optical Anomalies (Discrete losses)	Study manufacturing parameters for IC-Line in FY89/consider elimination of water-block in electro-optic strand
All	IC-Line speed is slow (20 FPM)	Plan to consider new weld techniques
All	Only one cable company can build AT&T's design	Plan to interest TRC in facilitizing to gain capability
WI-07,-08	Phosphor Bronze too expensive	Plan to investigate other alloys
WI-07,-08	Difficult to meet Manufacturing tolerances	AT&T may have to propose additional cable diameter increase

1.2 CENTER STRENGTH MEMBER DWT CABLE

The deep water trunk cable developed by AT&T at Simplex Wire & Cable is generically a Center Strength Member (CSM) cable. As can be seen in Figure 1, which shows an early version (circa 1983) of the 0.372" Miniature Lightwave Trunk (MLT) cable, the steel strength member wires are contained inside the copper tube conductor; i.e., in the "center" of the electrically conductive element. In fact, the steel wires are served about the plastic buffered fiber optic component, and become part of the "composite" electrical conductor by being in contact with the copper tube formed about the steel wires. The resulting composite electro-optic element has a 0.249" OD, the design of which has remained fairly constant, with certain exceptions to be discussed later, throughout the nine years of cable development.

1.2.1 Design Issues. In April 1986, AT&T re-designed the 0.372" MLT to become the 0.450" shielded trunk cable (see Figure 2), when it was determined that the 0.372" cable, which contained only a MDPE extruded insulation as protection for the electro-optic core, could not withstand certain "cold flow" and deployment testing. The cold flow tests were considered an indication of the ruggedness of the cable, and it appeared that the 0.372" cable could not readily be deployed from cable laying ships without incurring damage to the MDPE insulation. The cable appeared prone to electrical shorts either during and/or shortly after the deployment.

The 0.450" CSM/DWT cable contained as an additional design feature, an electrically conductive shield over the polyethylene (PE) insulation. This shield was in turn covered with an outer jacket of extruded high-density polyethylene (HDPE). The shield provided not only additional mechanical protection to increase the ruggedness of the cable, but also reduced the electromagnetic field signature of the cable by grounding of the conductive braid to seawater. The latter feature is believed to reduce the likelihood of attack by sharks.

In the first version of the 0.450" cable, a braided copper shield was used; however, it became evident that the braiding operation is relatively slow during manufacturing, which leads to an increase in the cost of the cable. In the next iteration design, the 0.450" cable used phosphor-bronze tube shielding as the outer conductor, which is the configuration shown in Figure 2. Prototypes WI-07 and WI-08 were built to this design.

By Spring 1988, it had become evident that the 0.450" CSM cable design had several remaining weaknesses. From the design standpoint, the voltage stress (>100 volts/mil) at the conductor/insulation interface was excessive with 4,000 volts DC voltage applied. AT&T maintained that the manufacturing tolerances associated with the 0.450" OD cable fabrication were too difficult to achieve in volume production. This led to the 0.525" CSM cable shown in Figure 3.

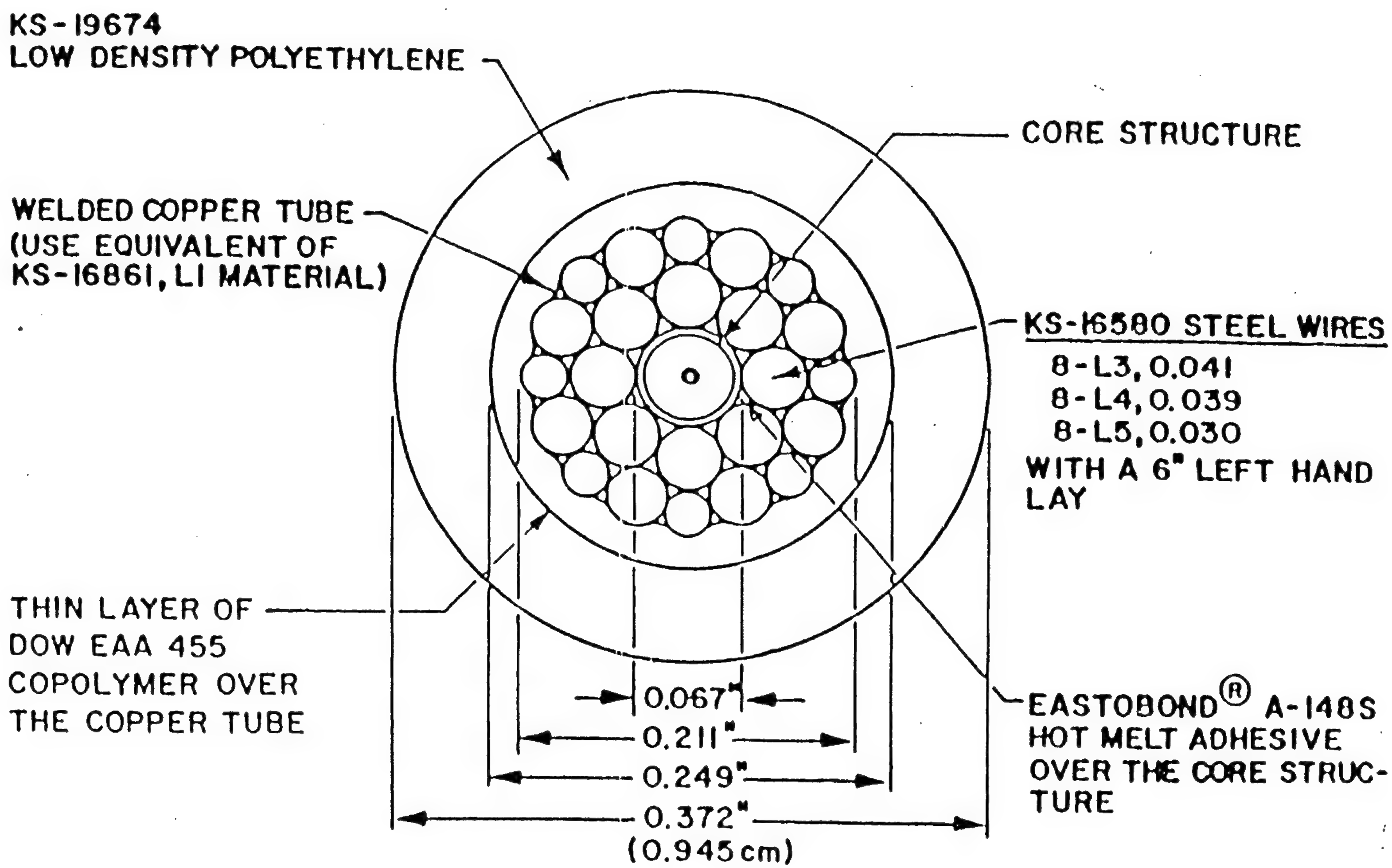


Figure 1. AT&T/Simplex 0.372" OD MLT Cable

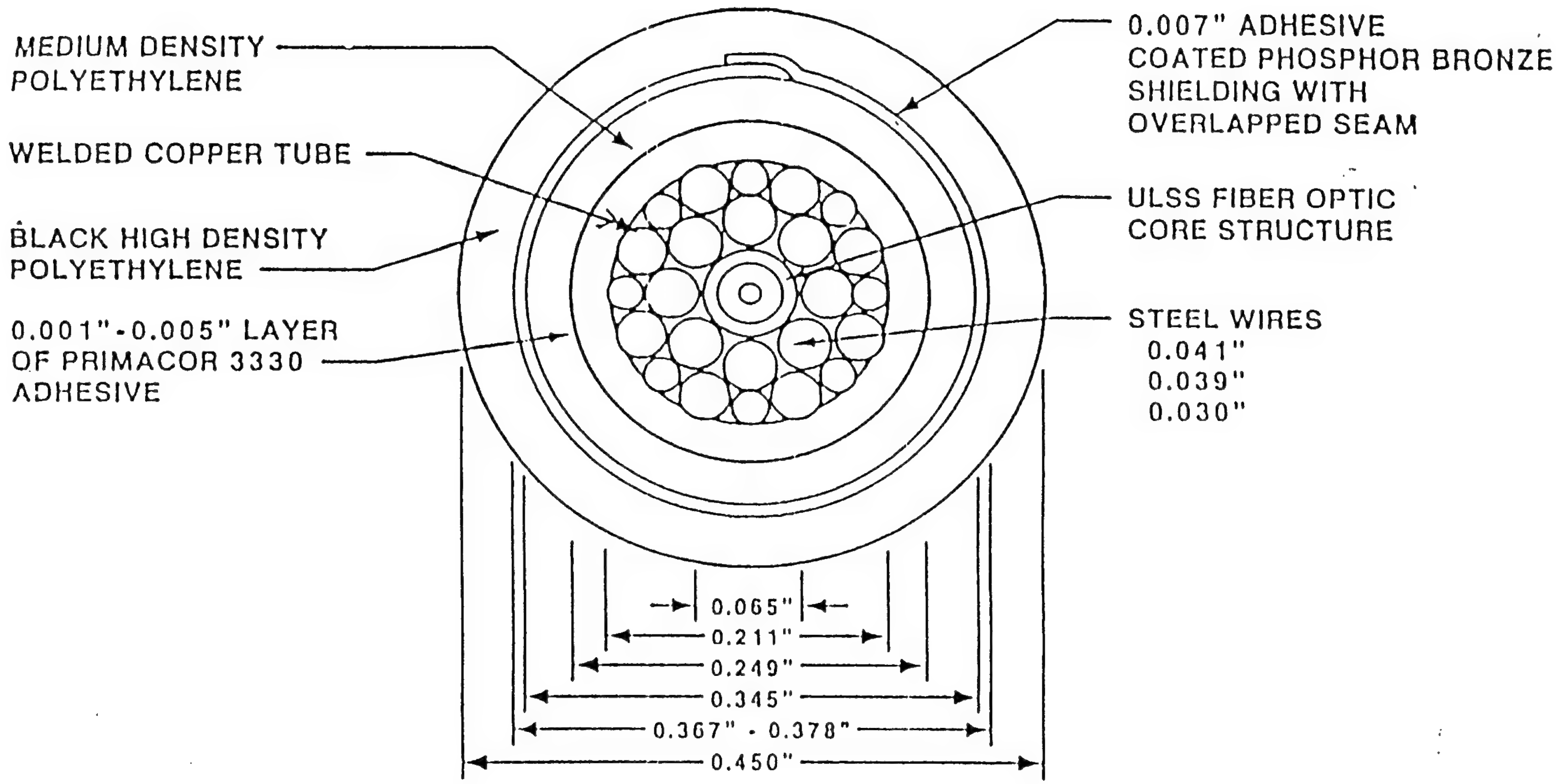


Figure 2. AT&T/Simplex 0.450" OD CSM/DWT Cable

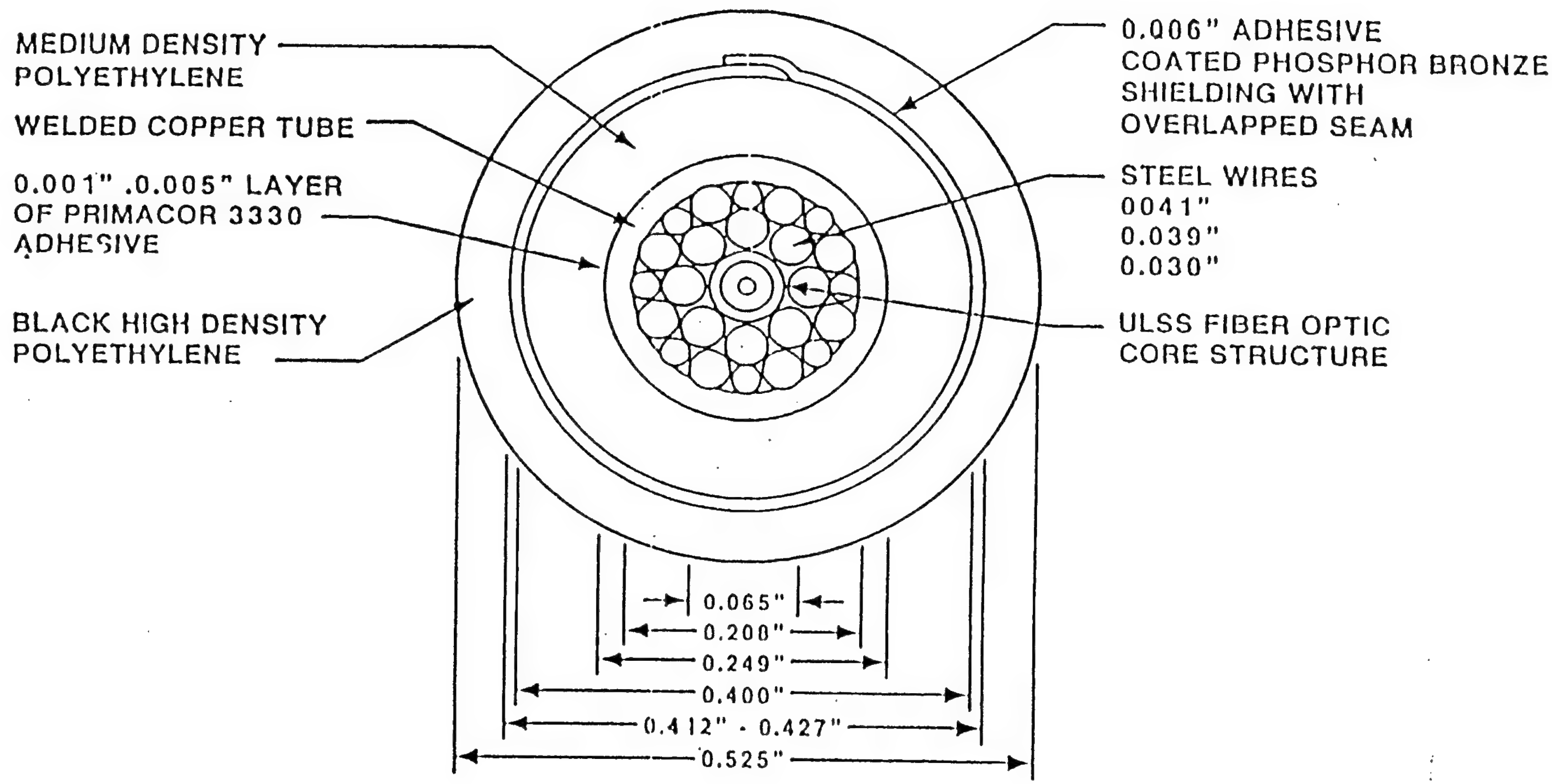


Figure 3. AT&T/Simplex 0.525" OD CSM/DWT Cable

1.2.2 Manufacturing Issues. Several of the manufacturing issues associated with the production of CSM/DWT cable were listed in Table 1. The first manufacturing process is the jacketing of the acrylate buffered fiber with an Hytrel extrusion followed by a Nylon extrusion (Figure 4). Both the ruggedness and the diameter of the buffered optical fiber must be increased to allow placement in the center of the steel strand. However, the Hytrel/Nylon extrusion jacketing is very difficult to perform and also results in an intrinsic possibility of inducing axial buckling into the glass fiber. Simplex Wire & Cable attempted to perform the Hytrel and Nylon extrusion jacketing through the WI-07 series of prototypes; however, they were never able to achieve uniform and consistent results. The optical attenuation in the completed cables was excessive, and contained discrete losses periodically throughout the length. Prior to the manufacturing of the WI-08 series, which began in late 1987, AT&T Bell Labs contracted AT&T Atlanta Works to provide the Hytrel/Nylon extrusion. Using state-of-the-art microprocessor-controlled extrusion equipment, the Atlanta Works was able to achieve a significant improvement in the quality of the jacketed fiber optics. Nevertheless, the optical fiber continued to experience axial buckling during the subsequent Inner-Conductor (IC) Line processing. This phenomena became known as "optical anomalies."

A schematic of the IC-Line is shown in Figure 5. This processing line is technologically the most advanced used in cable manufacturing, and also has the highest degree-of-difficulty. The line occupies a space that is nearly the length of a football field and about half the width of a football field. An extensive set of control methods and panels are required to insure coordination of all aspects of fabrication, since there are at least three major processes occurring simultaneously: (1) steel wire armoring, (2) copper tube rolling, shaping, welding, and reducing, and (3) swaging of the completed copper tube over the steel strand.

The steel wire armoring consists of a typical unilay steel wire rope configuration known as the Warrington strand. The diameter tolerances on the individual steel wires must be extremely strict, and further, the actual wires used must be measured and evaluated statistically to determine the loading sequence of the bobbins on the stranding machine. The closing die on the steel wire stranding machine is especially designed to insure that the individual wires as formed into the completed strand each have the exact same relative length with respect to each other, to prevent a loose wire from developing later during the copper tube swaging operation.

The copper tube forming mill is in-line with the completed steel strand, and the long rectangular copper strip is fed into the mill from a copper strip accumulator off to the side of the line. This accumulator allows the copper tape to be fed into the forming mill uniformly at the correct speed regardless of line stopping and starting. The ratio of the copper tape speed to the steel strand linear line speed is a critical manufacturing parameter, that must be monitored and controlled precisely to produce conforming copper-jacketed steel strand. The heart of the tube-forming mill is the

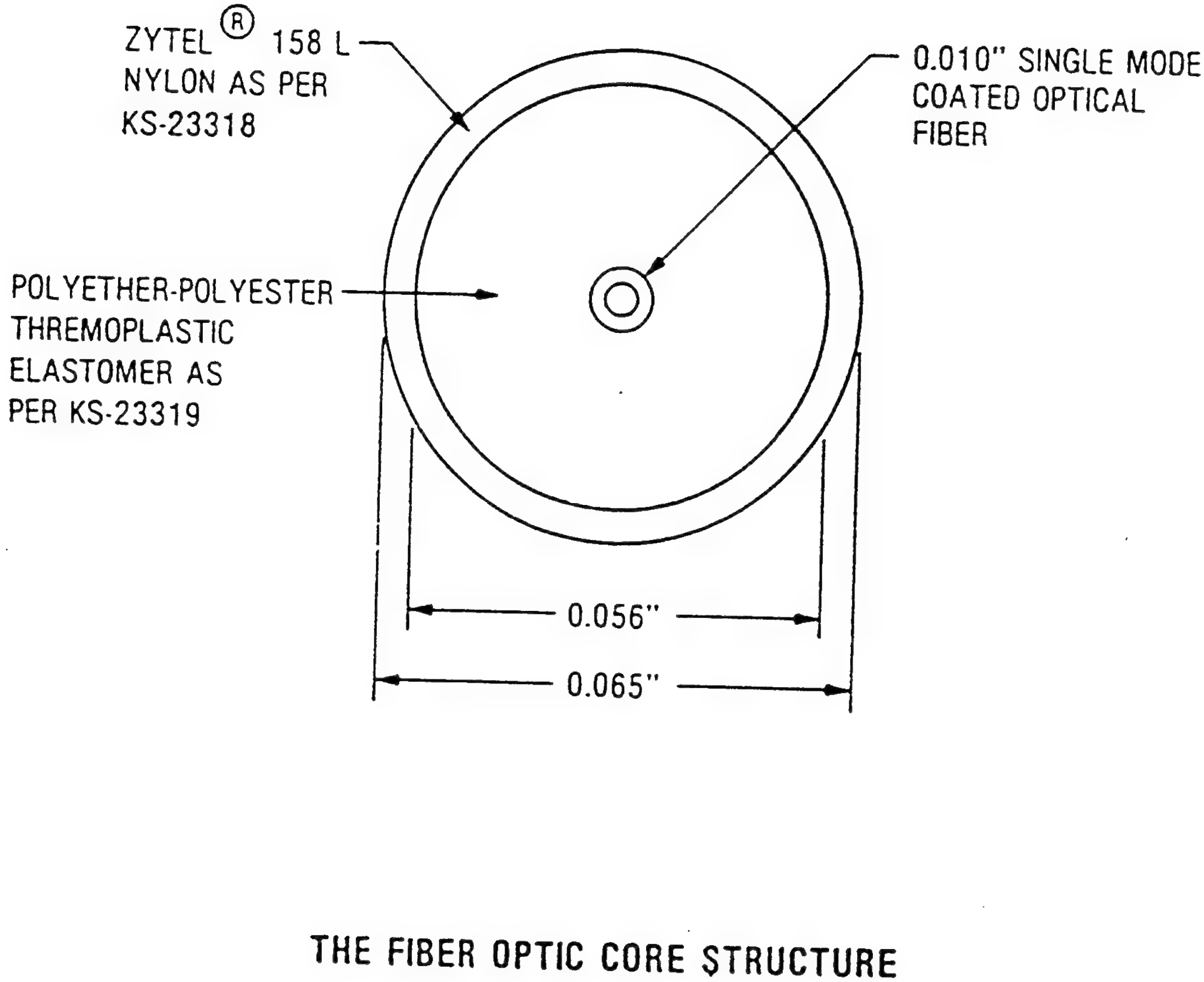


Figure 4. Hytrel/Nylon Jacketed Optical Fiber

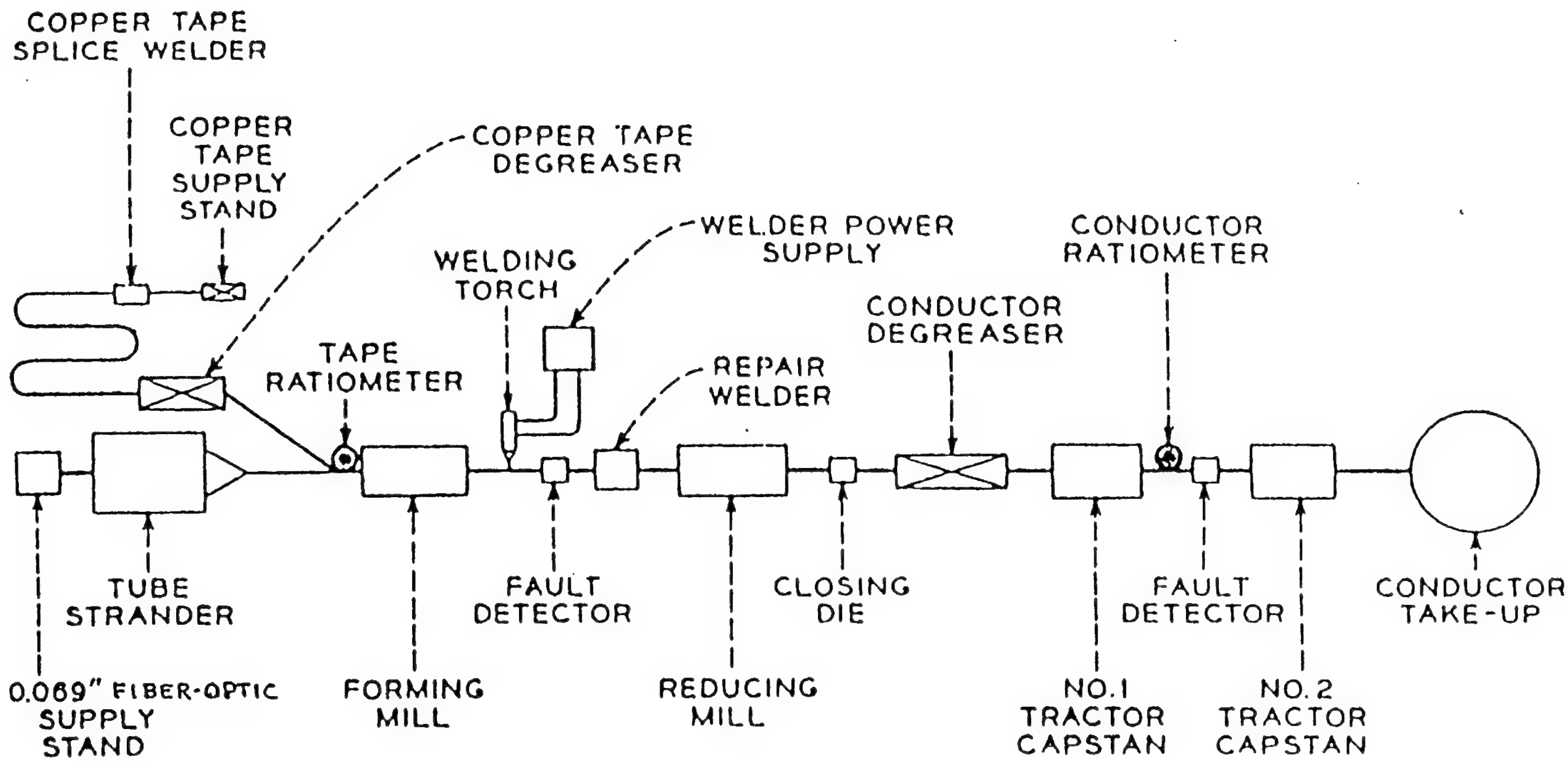


Figure 5. Schematic of IC-Line for CSM Cable

welding operation, which must hermetically seal the longitudinal seam of the formed tube. A great deal of technology is required to achieve the latter objective.

First, the copper strip itself must be oxygen-free copper, to preclude the formation of oxide or gas pockets under the heat of the welding torch. Four other aspects of the welding control problem are:

(a) Inert helium-argon shielding gas, with a high degree of purity and dryness, must be forced into the welding area to prevent electrode erosion and formation of whiskers on the electrode tip.

(b) All surfaces of the copper strip must be free from deposits of oil, water, or other contaminants which might otherwise contaminate the electrode tip and produce defects in the welded seam.

(c) The butted edges of the copper strip must be freshly slit; also they must be extremely level and exactly parallel while they are maintained under positive tension while passing under the welding arc. The series of rollers for forming, welding, and reducing the copper tube must be in exact alignment to insure that the butted seam is presented precisely at the position of the weld-point.

(d) The welder power supply requires special monitoring in order to control the weld current uniformly over long periods of time, in the precise ratio needed to correspond to a given line-speed of the formed tube as it passes through the weld-station.

The achievement of successful seam welding is thus a complex process involving tube forming, seam alignment, control of weld current, electrode positioning, and electrode tip materials and design. The control of the precise speed relationship of all the machinery and processes in the system is the key to an uninterrupted welding operation.

As can be seen in Figure 5, a fault detector just beyond the weld station is used to monitor the seam quality, and an in-line repair welder can be used to repair defects on the seam. If the formed copper tube contains surface defects off to the side of the seam, these can be corrected only <u>after</u> the reducing and swaging operation by stopping the entire line.

The swaging or die-sinking operation which occurs after tube diameter reduction is a critical point in the fabrication, because all of the manufacturing tolerances and processing steps come to bear at this time. If the steel wire sizes and forming methods are accurate, if the copper strip thicknesses and widths are just right, and if the speed of the copper strip area reduction just compliments the speed of the tube welding, then the ratio of the speed at which reduced copper tube is fed into the closing die with

respect to the linear motion of steel strand into the closing die will be such that the copper tube itself will be swaged or "extruded" into the outer interstitial space of the steel strand, to form a positive mechanical bond to the steel strand. The depth-of-penetration (DOP) of the copper tube into the steel strand intersticial space is an important manufacturing parameter that indicates the success of the entire operation. A known depth of penetration provides the degree of mechanical bond to the steel strand needed for cable deployment and operation under hydrostatic pressure. To insure proper DOP the difference in speeds between the steel strand and the copper is determined by monitoring the copper strip and the finished conductor with two photo tachometers. The ratio of speeds is also varied automatically as the conductor diameter and the copper tape thickness vary to maintain the required tube wall thickness after passing through the closing die.

The main problem associated with fabrication of the electro-optic strand on the IC-Line is the elimination of "optical anomalies," which are associated with axial buckling of the glass fiber at discrete places along the cable length. The optical anomalies occur periodically at intervals of several kilometers. The optical power is lost by relativistic scattering of light out of the waveguide while transiting these regions of extremely small radius of curvature of the optical waveguide. The optical anomalies occur about 50% of the time at places associated with starting and stopping of the IC-Line.

Since repeated optical anomalies are considered catastrophic to achievement of the cable optical performance requirements, the problem had to be solved. In the summer of 1989, several successful manufacturing trials, free of optical anomalies, were achieved at Simplex by deleting the water-block compound from the intersticial space inside the copper jacketed steel strand. Hence, the optical anomaly problem appears to have been solved **at the expense of having a non-water-blocked deep water trunk cable.** This may be the first modern deep sea cable without water-blocking. **The elimination of water-blocking may result in the need to replace an entire span length of cable in the event of cable damage to the copper tube.** Water entering the damaged cable, under hydrostatic pressure, will freely flood the entire inside of the cable. This will necessitate cable replacement. A second and more subtle potential problem is the long term internal response of the cable to hydrostatic pressure exposure. It is possible the plastic buffered fiber will be driven off its central, straight-line configuration, which could result in increased optical attenuation as a function of time.

Finally, another manufacturing issue associated with production of the CSM/DWT cable is the fact that only one cable company in the world, Simplex Wire & Cable, presently has the especially adapted IC-Line required to fabricate the relatively small-diameter (0.525" OD) cable. A second cable company, The Rochester Corp. (Culpepper, VA), has been working for over a year now to obtain the capability to manufacture CSM cable. By making an approximate $6.5 million facilities and capital equipment investment, they now have the

required machinery available, and are getting ready to operate it for the first time this summer. In view of Simplex's experience, there would appear to be significant risk to Rochester in getting their processes fully on-line and de-bugged in short order. A third cable company, the new STC Submarine Cable Systems facility in Portland, Oregon, plans to purchase the equipment needed to obtain CSM cable manufacturing capability in the near future. However, STC does not have previous experience with submarine lightwave cable built with the copper jacketed steel strand.

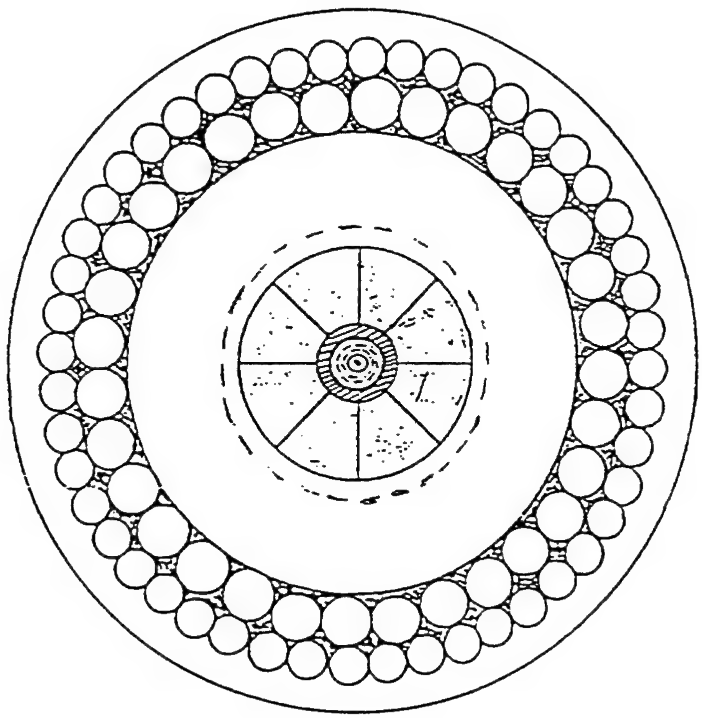
1.3 ALTERNATE DWT CABLE DEVELOPMENT PROGRAM

The issue of cable manufacturability by multiple vendors is the primary point-of-departure in the **Alternate FDS Cable Development at NOSC**. The alternate FDS cable was designed from the beginning, such that it could be fabricated by at least four or five cable vendors in the U.S. without any need for facilitization or equipment investment. The Alternate DWT cable being developed at NOSC is an outer-strength-member (OSM) cable, in that the steel strength member wires are placed outside of and over the electrically insulated electro-optic (E-O) core, as can be seen in the Phase I Model Design, Figure 6. The steel wires provide not only cable strength, but in addition, armoring protection for the E-O core. Consequently, the cable is intrinsically much more rugged than CSM cable. The OSM cable employs a unique electro-optic strand in the center of the cable, consisting of an hypodermic needle-sized steel tube encasing the optical fiber, which element is in turn surrounded by copper conductors. The steel tube encapsulation of the optical fiber is the only relatively high-technology process; afterwards, the copper stranding, electrical insulating, steel wire armoring, and outer extrusion jacketing are all conventional cabling processes that have been around for fifty to one hundred years. Further, the steel-tubed fiber process is not so elaborate or difficult as the IC-Line operation discussed above for CSM cable fabrication. The Alternate Deep Water Trunk (ADWT) cable development at NOSC was originally conceived in three distinct phases. The Phase I development was to prove that several vendors in the U.S. have the capability of putting the steel tubed fiber into a conventionally fabricated cable. Phase II intended to prove that at least two or three vendors have the capability of building this type of cable in multiple kilometer lengths (10 to 20 km range).

1.3.1 Phase I: OSM/Steel Tubed Fiber Cable. The Phase I effort succeeded in establishing conclusively that the OSM cable, incorporating a central steel tubed fiber element, is a viable design for the FDS deep water trunk cable application. Furthermore, from Phase I cable testing it became evident that one can easily build OSM cable using the steel tubed fiber, such that it exhibits cable performance characteristics surpassing those of the CSM cable. In fact, all of the major design and manufacturing

COMPOSITE E-O CONDUCTOR:	
Single Mode Fiber	
8/125 Glass.......	0.005"
UV-acrylate.......	0.010"
Steel Alloy Tube	
Void-fil gel......	0.027"
Laser welded OD...	0.032"
Shaped Copper Strand	
> #7 AWG compacted	0.155"

2) INSULATION STRUCTURE:	
EAA-copolymer....	0.165"
MDPE dielectric..	0.280"
3) DOUBLE-STEEL ARMOR:	
28/0.032" GXIPS..	0.344"
46/0.023" GXIPS..	0.390"
4) OUTER HDPE JKT...	0.468"



ELECTRICAL PROPERTIES:
DC Resistance = 1.5 ohms/km
Rated Voltage = 4,000 VDC

OPTICAL PROPERTIES:
Atten(1300nm) = 0.50 dB/km
Atten(1550nm) = 0.28 dB/km
Disp'n (1300) = 2.5 ps/nm-km
Disp'n (1550) = 19.0 ps/nm-km

MECHANICAL PROPERTIES:
BS.min = 12,540 lbs
WL = 5,000 lbs
e(WL) = 0.6% max
Torque @ WL = 24 in-lbs
Rotation @ WL= 360 deg/kft

PHYSICAL PROPERTIES:
OD = 0.468"
WT/air = 265 lbs/kft

Figure 6. NOSC's Alternate DWT Phase I Model Design

issues associated with the CSM cable (summarized above in Table 1) are intrinsically eliminated in the OSM/steel tubed fiber cable approach.

As can be seen by comparing Figure 7, which shows the steel tubed fiber encapsulation process, to Figure 5 which shows the IC-line process, the steel tube encapsulation process for optical fiber is much simpler, smaller, and more straight forward. Since there is no attempt to integrate three processes into one line, the control and monitoring problems are reduced to a minimum. For example, there is no steel wire armoring section, and no tube swaging operation. The line is rather a single tube rolling mill, that utilizes laser welding to seal the longitudinal seam of the steel tube. The only new aspect is the feeding into the center of the tube of an optical fiber. This fiber is protected during welding by an extremely small-diameter "insertion tube," which guides the fiber optic into the center of the newly formed steel tube. After the welding of the seam, the steel tube is reduced to a smaller diameter, monitored for weld integrity, and then taken up on a conventional takeup reel. Once the optical fiber is encased in this steel tube, it is extremely well protected for subsequent handling and machine processing required to complete the remaining cable fabrication steps.

The **remaining steps, as mentioned earlier, are all conventional cable processing operations, which can be performed by many cable vendors,** using the same equipment that is used to produce many different types of cables. Consequently, the requirement for a cable that can be produced by multiple vendors is automatically solved as soon as the fiber optic is placed into the small diameter steel tube. The encapsulation of optical fibers in a small diameter steel tube can be done by at least two distinct suppliers: (1) Laser ArmorTech, and (2) Helios, Inc.. Furthermore, Laser ArmorTech Corp. has licensed several other foreign companies. Laser ArmorTech will also license their process to U.S. cable manufacturers for the purpose of making a specific product; i.e., the <u>alternate</u> FDS-UWS cable.

1.3.2 Phase II: Long Length Manufacturability. The remaining issue with respect to the OSM/steel tubed fiber cable fabrication concerned the proof that multiple cable vendors, using available conventional equipment, could build the cable in long lengths. The primary purpose of the remainder of this report is to demonstrate that such a proof has now been given. The Phase II OSM/steel tubed fiber cable development, in practice, consisted of the manufacturing of three (3) relatively long, continuous lengths of ADWT by three respective, independent cable vendors. The design and manufacturing of these lengths, which is discussed in detail in Section 3.0 below, demonstrated that NOSC's ADWT cable was able to satisfy the original FDS Program Office requirement: "...develop a DWT cable design having the capability of being manufactured by multiple vendors."

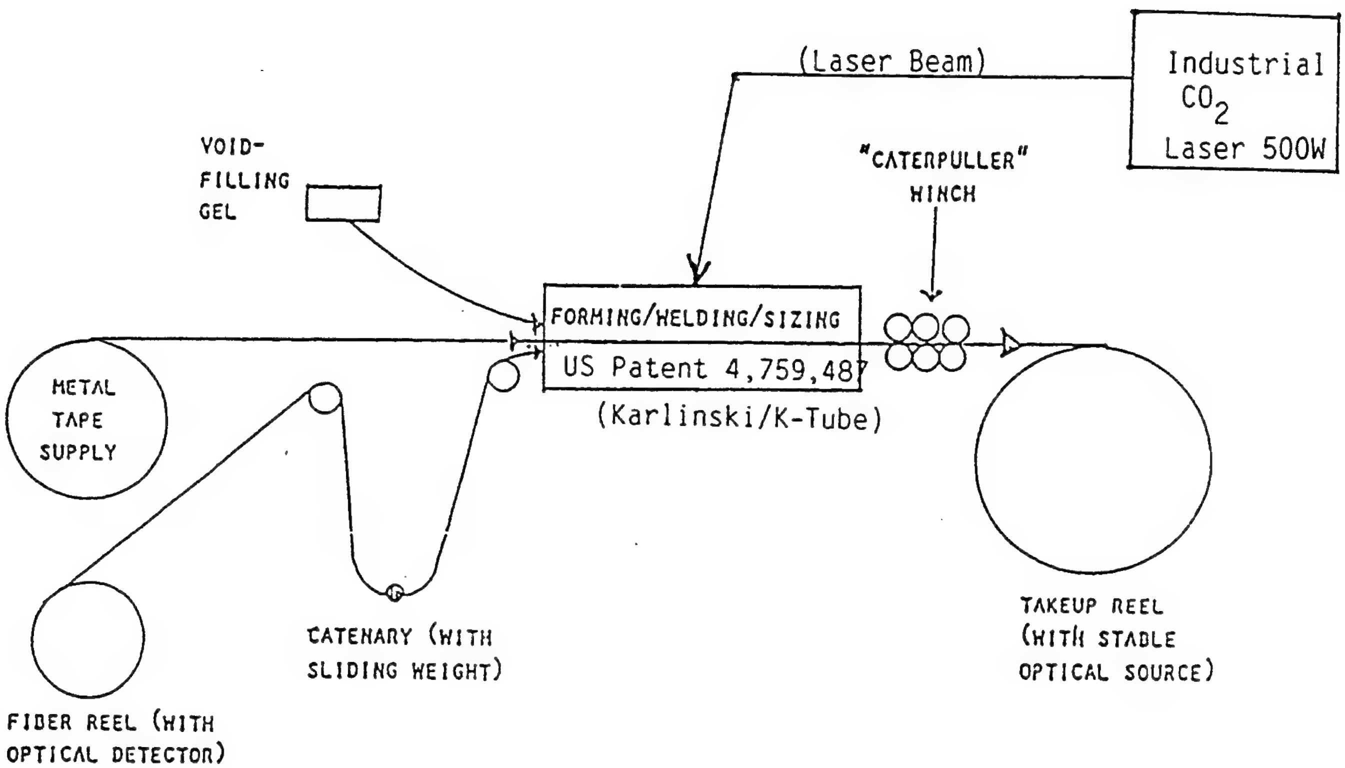


Figure 7. Steel Tubed Fiber Optic Processing Line

The three cable vendors accomplished this in spite of AT&T's prediction in May 1989 that it would require at least two (2) years more development before the alternate cable would be produced in greater than 5 km lengths. In fact, **by May 1990, one year later, NOSC had received and tested a total of 38 km of alternate DWT cable that not only met the original FDS cable requirements, but in addition, exceeded all of the optical and mechanical performance requirements by at least 50%.**

2.0 PHASE I ALTERNATE DEEP WATER TRUNK CABLE DEVELOPMENT

Phase I development intended to prove the design concept of a steel tubed fiber in a torque balanced outer strength member armor package. The testing in Phase I simulated operational conditions in the laboratory. To prove the design concept, three suppliers fabricated one kilometer sample lengths. The Phase I designs are summarized here to provide continuity for the discussion of the evolution of the Phase II designs. Further details regarding the Phase I designs may be found in the Phase I testing report entitled "Phase I Test Results: Alternate Fixed Distributed System Underwater Segment Deep Water Trunk Cables," dated 30 September 1989. Manufacturing concerns as well as test results and method were incorporated into that document.

2.1 ALTERNATE CABLE PHASE I SPECIFICATION

The Model Design used for the Phase I cable development was contained in NOSC's "Specification for Seafloor Electro-Opto-Mechanical Cable," Revision A, dated 8 July 1988. NOSC placed a Delivery Order with Western Instrument Corp., who used this "EOM Cable Spec" to solicit proposals from potential manufacturers. The model design for the seafloor EOM cable was shown earlier in Figure 6. The electro-optic core consists of a single axially placed optical fiber encased in a steel tube, surrounded by stranded copper and an extruded dielectric material, medium density polyethylene (MDPE). In the outer strength member design, two layers of steel protect the electro-optic core and provide torque balanced strength.

2.1.1 Key Design Feature: Copper Stranded Steel Tube. The electro-optic core of the ADWT cable is significantly different from the CSM designs. Instead of placing the strength member around the delicate plastic buffered optical fiber, the ADWT protects the fiber within a hypodermic needle-sized steel tube. The key design feature of the ADWT is the steel tube: this tube ensures protection for the optical fiber, both during manufacturing and during cable deployment and handling. The steel tube protects the optical fiber from radial compressive forces of the copper strands and the other cable elements during cable loading. The thixotropic void filling gel surrounding the fiber within the steel tube distributes radial compressive forces, preventing microbending losses. The shaping of the copper strands maximizes the area of copper for a given outer diameter; thus, the diameter needed to obtain low DC resistance over long lengths for electrical power transfer is minimized. The cable's overall diameter is minimized with shaped segmented stranding, however, the option of round copper wire provides the tradeoff of better flexibility and bending strain relief for the copper. Both options were allowed in the EOM cable spec's model design, and both approaches were pursued.

2.1.2 Manufacturing Methods and Concerns. An important issue at the time of the Phase I development was the question of whether or not undersea fiber optic cable could be built on conventional cabling equipment, hence alleviating the need for a $6-12 million

capital equipment investment. The small-diameter steel tube to encapsulate the optical fiber is the key to enabling this possibility. Hence, in Phase I a great deal of time was spent evaluating the methods for encapsulating optical fiber into the small-diameter steel tube. These investigations consisted of both technical feasibility, and economic cost studies to determine the likely selling cost of steel tubed fiber in the event of transitioning into production manufacturing.

The steel tubing process at Laser ArmorTech, Inc., in San Diego, CA, appears to be a well established, high reliability process that is technologically simple, and which produces steel tubed fiber at a relatively high rate of speed: 85-100 FPM (versus the 20-30 FPM of the IC-Line which makes center strength member cable at Simplex). This process has been licensed to Ocean Cable Company (OCC) in Japan, to Philips in Germany, and to Telephone Cable Ltd (TCL) in England, and a license is presently being negotiated by Alcatel/Cable de Lyon in France. These licensing agreements included setting up all of the required manufacturing equipment and providing training for the operators. The reported cost of the manufacturing equipment, including the high power industrial CO_2 laser was about $400k.

There is a competing but similar manufacturing process being used by Helios, Inc. (a division of KKD Steel) in Tokyo, Japan. Laser ArmorTech claims that Helios is violating their U.S. Patent No. 4,759,487 (dated 26 July 1988, H. Karlinski); however, the eventual outcome of that debate is unknown. In any event, the laser welding of the small diametered steel tube about the optical fiber is a well established manufacturing operation at this time. Due to the licensing agreements that have occurred, the product will soon be available from multiple vendors. In addition, Laser ArmorTech, Inc. supplies all U.S. cable companies indiscriminately.

Confidence for the use of the small-diameter steel tubed fiber in the Phase I EOM cable design was gained by previous evaluation of the steel tubed fiber product on a stand alone basis by NOSC Hawaii Lab in 1986-87. At that time, ten (10) independent 10 km lengths of steel tube containing one optical fiber were purchased, scrutinized during fabrication, and later tested in the laboratory. From this testing, it was determined that the steel tube fiber could withstand 10 kpsi pressure without suffering excess optical attenuation.

The Phase I cable fabrication indicated that the steel tubed fiber element could easily withstand the stress of conventional cabling machinery and/or handling stress in a conventional cable plant. In contrast, one Phase I cable built by The Rochester Corp (TRC), that did not use the steel tubed fiber optic element, displayed catastrophic failure of the Hytrel/Nylon buffered fiber. The optical fiber itself was AT&T's <u>hermetic</u> fiber, which contained several Angstroms of amorphous carbon deposited on the outer surface of the glass cladding. The reason for multiple breaks in the optical fiber was not determined conclusively, but it is clear that the steel tubed fiber optic element is virtually "bullet

proof" from the standpoint of fabrication using conventional cabling equipment, whereas the plastic buffered fiber requires a great deal more care. One year later, TRC successfully manufactured a Phase I cable without the steel tubed fiber. This manufacturing re-run did not use hermetic fiber, however. A standard AT&T depressed-clad fiber with dual acrylate coating was further jacketed with Hytrel and Nylon (see Figure 4).

2.2 PHASE I CABLE PROCUREMENT AND AWARDS

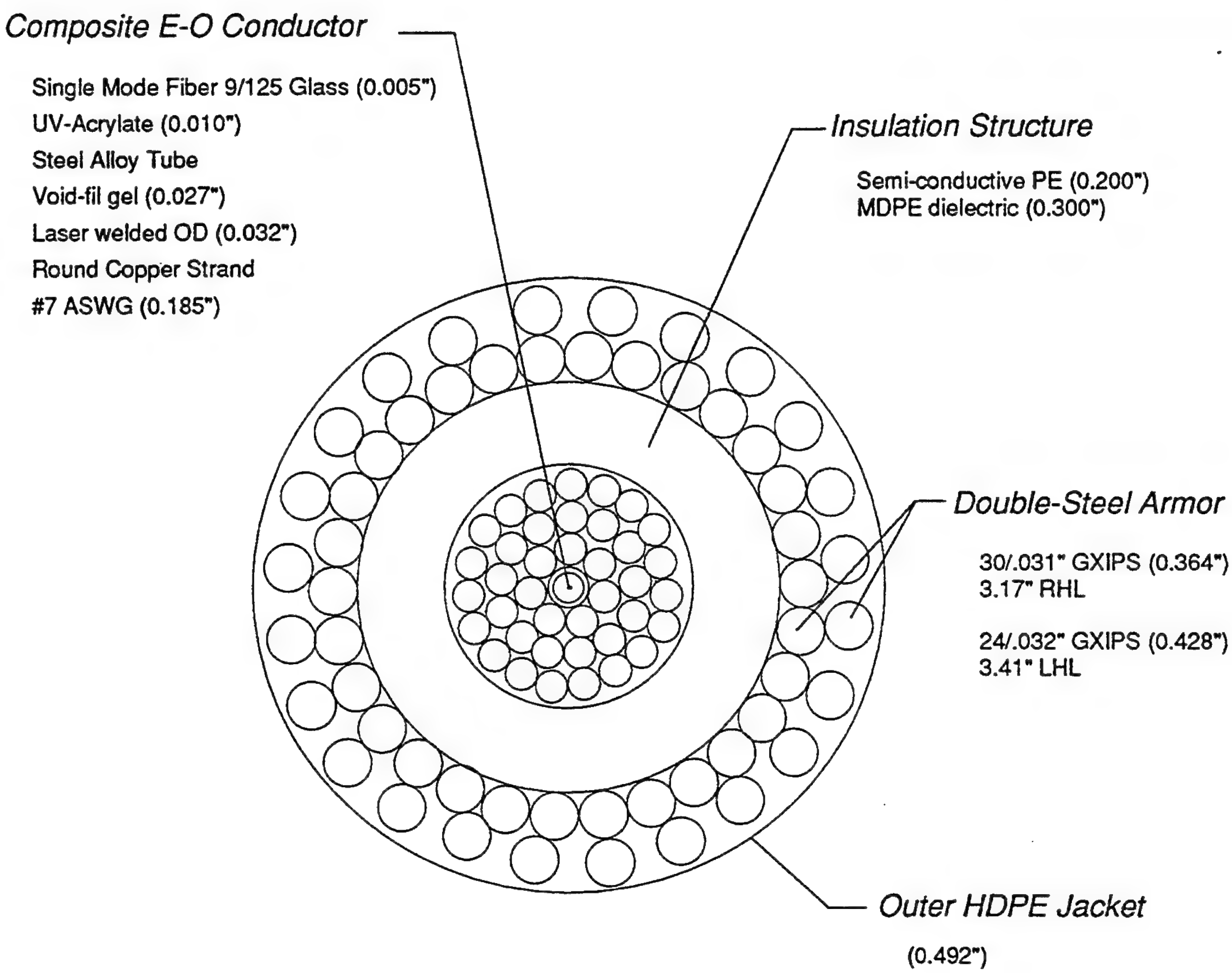
The Phase I Model Design Rev. A was sent to prospective cable manufacturers in August 1988. The returned proposals were reviewed and three vendors were awarded contracts in September 1988 to build one kilometer prototype lengths for testing and evaluation. Consolidated Products Corporation, The Rochester Corporation and STC Submarine Cable Systems in England were each awarded contracts through Western Instruments Corporation.

2.3 CONSOLIDATED PRODUCTS CORPORATION: SB-37945

The cross section of the 1.066 km Phase I ADWT cable from Consolidated Products Corporation is displayed in Figure 8. Consolidated's cable design is built in accordance with one of the options allowed in the EOM Cable Spec (REV A) Model Design: round copper wires stranded in three layers about the steel tube. The armor package utilized the specified 0.032" GXIPS steel armor wires in the first layer; however the second layer used these same sized wires in a "spaced armor" configuration. Otherwise, the design followed the guidelines of the Rev. A Specification. No catastrophic problems were encountered during manufacturing, although CPC did experience externally imposed difficulties early in fabrication when a snow storm knocked out the power in the manufacturing plant. The MDPE insulation was being extruded at the time, which caused the run to be aborted, and necessitated stripping off the plastic and the copper stranding back to the steel tubed fiber stage. They then started over and were able to fabricate the cable successfully. This incident demonstrated the ruggedness of the steel tubed fiber element. If the fiber element had been buffered with plastic, it would have been destroyed.

2.3.1 Composite Electro-Optic Strand. The stranding of the copper around the steel tube containing the optical fiber was in accordance with the option of using round copper wire stranding (para. 4.3.2.2) in the Model Design. Instead of shaped segments, Consolidated used three layers of #23 AWG round, bare copper wire. The process of stranding this core was rather slow however. Two passes were required instead of only a single pass: two layers with seven and thirteen wires, respectively, were applied in the first pass, and the remaining 23 strands of the third layer were applied in the second pass. A semi-conductive layer was extruded over the copper under the dielectric to ensure low voltage stress at the conductor/insulation interface. Even though this design proved to meet the electrical performance requirements, the rate of

Consolidated Phase I



Electrical Properties

DC Resistance ≤ 1.5 ohms/km
Rated Voltage = 4,000 VDC Nominal

Optical Properties

Attenuation (1300 nm) ≤ 0.50 dB/km
Attenuation (1550 nm) ≤ 0.28 dB/km
Disp'n (1300) ≤ 2.5 ps/nm - km
Disp'n (1550) ≤ 19.0 ps/nm - km

Physical Properties

OD = 0.492" (0.500" max.)
Weight in air ≤ 280 lbs/kft.

Mechanical Properties

Min. Breaking Strength = 11,300 lbs
Working Load = 3,000 lbs
Max Elongation @ W.L. = 0.6% max.
Torque @ W.L. ≤ 2.4 in.-lbs.
Rotation @ W.L. ≤ 360 deg/kft

Figure 8. Consolidated Products: Phase I Alternate DWT

copper stranding was about 30 FPM--which is not much improvement over the IC-Line which makes the inner conductor in the CSM cable. Therefore, Consolidated proposed to redesign the stranding for Phase II. In the Phase II cable from CPC, only two layers of copper were used, which were applied in a single pass at a higher rate of speed (about 40 FPM).

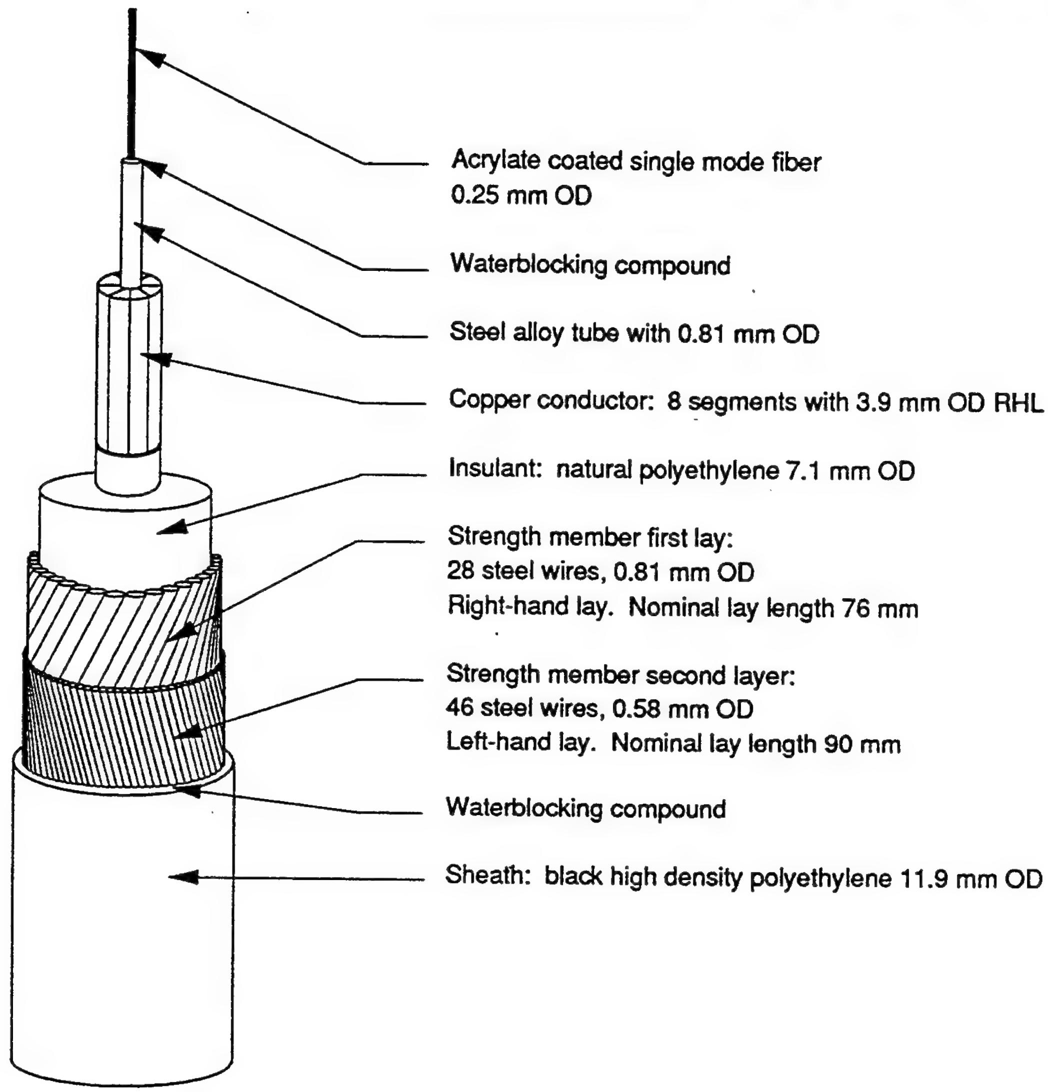
2.3.2 Torque Balanced Steel Armor. The armor design used by Consolidated utilized a spaced armor in the outer layer, which constituted a minor deviation from the Model Design. The spaced armor was proposed so that the outer jacket and the armor would be integrally fused by pressure extrusion of the outer HDPE jacket. Also, it is believed that the "spaced" armor construction provides intrinsically more internal stress relief within the outer layer wires when the cable experiences axial twist during coiling into the hold of a cable laying ship. Although the spacing of the wires was not totally uniform, the mechanical performance of the cable was extremely good.

2.4 STC SUBMARINE CABLE SYSTEMS: SEAFLOOR EOM CABLE

Figure 9 shows a cross section of the cable delivered to NOSC for Phase I. The 1.195 km length delivered (out of a 5 km continuous length manufactured) by STC employed the same steel tubed optical fiber component (from Laser ArmorTech, Inc.) as used by Consolidated Products.

2.4.1 Composite Electro-Optic Strand. The electro-optic core of the Phase I STC cable has six stranded #16 SWG (British Standard Wire Gage) copper wires (0.064" ea.) around the Laser Armor Tech steel tube. These copper wires were stranded through two nested closing dies, which gradually achieved some deformation of the individual wires, and some diameter draw down, such that the six wires could be compacted into a relatively smaller space with a smaller overall diameter. STC intended to compact the copper wires so that they seated on the steel tube; the closing die was not small enough to achieve this however. The steel tube was not mechanically linked to the copper, but was loose and could be pulled out by hand from an open end. No load transfer can occur between these elements, since they do not have integral contact. It is not clear whether the "uncoupled" nature of the steel tube with respect to the surrounding cable structure would be a problem operationally; however, during cable testing an epoxy plug was used to cement the outer surface of the steel tube to the internal surface of the copper stranding. This prevented the steel tubed fiber optic component from withdrawing internally into the cable structure whenever the surrounding cable structure elongated due to axial tension loading. Although such an approach could be used for operational terminations, in practice, STC agreed with the Navy that the Phase II cable should be configured to provide more contact between the steel tube and the surrounding copper stranding structure. In fact, this did occur in Phase II.

STC Phase I



Nominal Physical Characteristics of Cable

Seafloor Electro-Opto-Mechanical cable

Sheath outer diameter	11.9 mm
Total cable weight in air	0.395 kg/m
Total cable weight in water	0.281 kg/m
Specific gravity	3.56
Stowage factor	0.16 m^2/km
Minimum U.T.S.	46 kN
Nominal Tensile Stiffness	5.8 MN
Hydrodynamic constant	0.53 Rod m/s
Minimum bend dia. (Finished Cable)	1.0 m
Minimum Load at 1% strain	40 kN
Composite Power Feed Conductor Resistance	<1.5 ohm/km @ 20° C
Insulation Resistance	>3.5 x 10^9 ohm - km
Composite Power Feed Conductor Capacitance	0.215 μf/km

Figure 9. STC: Phase I Alternate DWT Cable

2.4.2 Torque Balanced Steel Armor. The armor package used in the STC cable matches the Model Design. The inner layer has 28 wires; the outer layer 46 wires. STC did have problems obtaining good preform in the relatively small outer layer wires. As a consequence, the impressions of some high wires can be seen through the outer jacket--although none of the wires actually penetrated through the surface of the jacket. It can be concluded that the model design's use of 0.023" GXIPS wires at about 17-18° only marginally allows preform. STC used nearly an 18° lay angle in the second layer. Consequently, the only way to achieve improved preform would be to increase the lay angle--which is not advised--or to increase the size of the wires in the second layer. In Phase II the Model Design was modified to employ a smaller number of larger wires in the second layer to enable better preform. The tradeoff in doing this is that the diameter over the second layer of steel tends to increase, which necessitates that the outer jacket thickness is decreased when the overall cable diameter stays constant. Also, it should be obvious that larger wires tend to increase the torque contribution of the second layer, which must be compensated by increasing the torque contribution of the first layer. The latter can be achieved only by increasing the first layer wire diameter and/or increasing the first lay angle. All of these tradeoffs were considered in obtaining the Phase II design.

2.5 THE ROCHESTER CORPORATION

The Rochester Corporation was the only manufacturer that did **not** employ a steel tube to protect the optical fiber; further, they were the only manufacturer whose cable failed the optical tests. Rochester chose to use a Hytrel/Nylon buffered fiber in place of the steel tube. The remaining construction of the cable followed the model design very closely. Rochester was the only manufacturer in Phase I who used the shaped segmented copper stranding about the fiber optic core element. The cable cross section is shown in Figure 10.

The first cable from Rochester sent to NOSC in early 1989 had numerous optical anomalies and fiber breaks. The optical fiber itself was hermetic fiber purchased from AT&T. Rochester initially stated that they believed that the hermetic fiber was substandard, and that the breaks resulted from using hermetic fiber. They stated that several samples of the cable containing fiber breaks were sent to AT&T for evaluation. Rochester stated that AT&T evaluated the fiber and concluded that nothing was wrong with the fiber.

Later, Rochester reported to the Navy that the breaks were the result of a typographic error on the production planning, which resulted in 10 times more tension on the optical fiber during manufacturing than intended. Attempts were made by NOSC in the laboratory to reproduce this possible failure mechanism by applying the 10 lbs tension suggested by Rochester, but the failure mode could not be reproduced. Also, various combinations of tension and temperature did NOT succeed in reproducing the type of fiber break observed in the Rochester cable. Also, Rochester was unable to

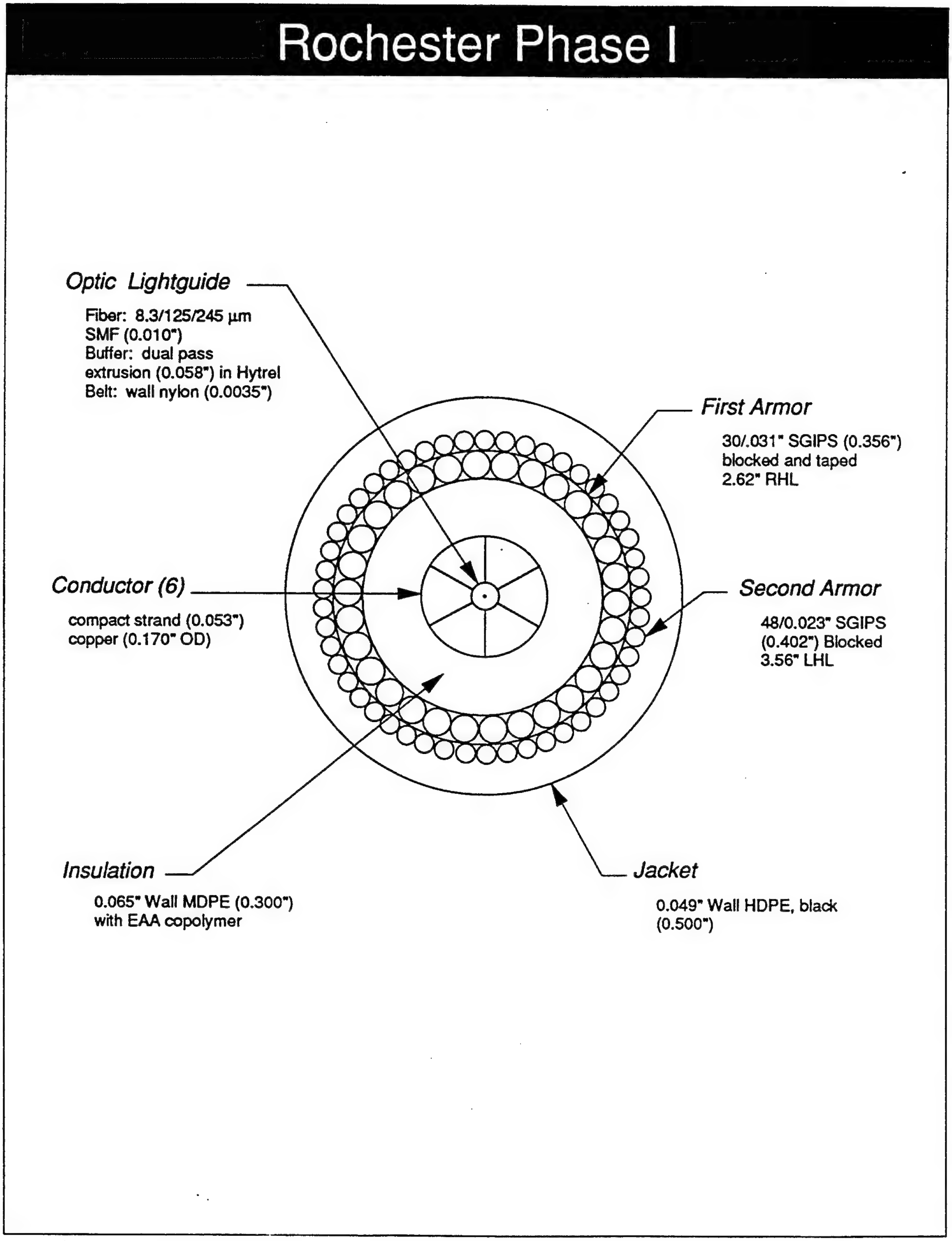


Figure 10. TRC: Phase I Alternate DWT Cable

make available any in-process inspection records for the fiber optic element--such that it was impossible to know whether the breaks occurred during (1) the Hytrel extrusion over the acrylate coated fiber, (2) the Nylon extrusion over the Hytrel, (3) the copper stranding over the Hytrel/Nylon coated fiber, or (4) the MDPE extrusion over the copper stranded fiber optic element.

A replacement cable was sent to NOSC in January of 1990. The replacement was both optically and mechanically sound; however, the **replacement cable employed standard optical fiber**--AT&T's depressed clad fiber--**not** hermetic fiber. Because Rochester communicated very little information about their manufacturing processes or the problems encountered, **it is impossible to know whether the success was due to deleting the hermetic fiber** and using standard fiber instead, or whether the "new" processing parameters would work equally well **if Rochester had elected to continue with hermetic fiber.** <u>**One thing is clear: hermetic fiber has not been shown to be compatible with the Rochester cable approach; further, the Rochester cable, using standard fiber in Phase II, is NOT compatible with the long term undersea application**</u>. The Rochester design, without the steel tube, does NOT include any hermetic barrier to protect the optical fiber from hydrogen and water.

2.5.1 Hytrel/Nylon Buffered Fiber. Rochester chose to use a buffered fiber, a buffer similar to that in the AT&T/Simplex CSM design, in place of the steel tube. The buffer over the fiber was a Hytrel extrusion over a UV-acrylate coated single mode fiber, with a thin Nylon coating over the Hytrel. The buffer outer diameter was 0.065". Rochester performed the buffering at their own manufacturing facility. As stated above, Rochester was unable to deliver any in-process records showing whether or not the fiber optic had been broken during this process. The Phase I cable spec demanded that such in-process tests occur in accordance with Quality Control procedures as outlined in MIL-I-45208. According to the latter, the U.S. Navy had the right to inspect these records. If these tests were not made, then Rochester failed to follow the requirements of the contract. If the in-process optical measurements were made--and Rochester merely chose NOT to make them available to the Navy--then Rochester was in violation of the terms of their contract which accepted "source inspection" and MIL-I-45208 Inspection procedures. Either way, Rochester's inability to provide in-process inspection records for the optical fiber and their inability to shed light on the fiber breakage problem--combined to frustrate any possibility of definitive conclusions with respect to developing an outer strength member cable using hermetic fiber within a plastic buffer package.

2.5.2 Composite Electro-Optic Strand. The shaped segmented copper conductor design in the Model Design was only attempted by Rochester. They elected to use only six segments instead of eight however. Due to the success of the replacement cable (received a year later during Phase II testing), it appears that there are no manufacturing problems associated with using **a standard telcom grade fiber within the Hytrel/Nylon buffer--at least in this <u>short length</u> run,** for placement within the shaped, segmented copper

stranding. Finally, Rochester would not tell the Navy the processing speed for the shaped segmented copper construction, such that it is impossible to know whether Rochester's approach would be of interest in the future. The dielectric extrusion around the copper was slightly thinned in a few regions of the cable. No electrical performance degradation was observed at the necked-down regions, however.

2.5.3 Torque-Balanced Steel Armor. The armor package used by Rochester contained the most numerous and smallest diameter wires. The inner layer contained 30 wires while the outer layer had 50 wires. Good preform and good performance was obtained from this steel armor construction. Only a few minor anomalies could be seen through the outer jacket. The cable demonstrated very low torque and rotation--and the highest break strength of any Phase I cable.

2.5.4 Replacement Cable. The replacement cable which arrived in January of 1990 was tested with the Phase II cables and the results will be included in the Phase II test report. The cable was built <u>similar</u> to the first damaged cable, with the same dimensions and materials--**and the exception of using <u>standard</u> telcom grade fiber versus hermetic fiber.** Since the cable was built to Phase I specifications, it is considered a Phase I cable despite the coincident testing with the Phase II cables.

The cable had low loss which was uniform throughout the cable, proving that Rochester does have the capability to produce this type of cable--at least in short lengths. However, it is unlikely such a cable would be suitable for a long term undersea application since **there is <u>no hermetic barrier in the cable to protect the optical fiber</u>.** As noted above, it is impossible to determine whether the cable could have been made successfully with hermetic fiber. The electrical and mechanical properties of the cable met all specifications.

2.6 CONCLUSIONS AND RECOMMENDATIONS FROM PHASE I

The results from the manufacturing of the Phase I cables determined that the basic design, which employs the steel tubed fiber optic element on the cable axis, performed as well as or better than expected, and that **<u>multiple vendors can produce the Model Design cable on conventional cabling equipment--without any need for the high capitalization expense associated with CSM cable production</u>.** The success of the manufacturers in Phase I led to continuation of the ADWT design for long length manufacturing trials in Phase II.

When the FDS mission requirements were reassessed by NOSC at the end of Phase I (May 1989), it was determined that greater strengths would be needed from a Deep Water Trunk cable in order to support cable deployment and recovery (into depths $\geq$ 10 kft) using conventional, commercial state-of-the-art techniques. This marks a dramatic point-of-departure for the Alternate FDS cable development compared to the "mainline" AT&T center strength member cable development.

It is significant to note that the strength of the AT&T CSM cable cannot be increased without scrapping the entire CSM design and starting over. In addressing the issue of cable recovery from deep water, AT&T proposed the use of <u>advanced</u> recovery techniques, i.e., "cable recovery with overrun," which alleviates the need to increase the strength of the CSM/DWT cable. In other words, AT&T chose to retain the weaker cable design, depending on the hope of using the advanced recovery technique.

NOSC chose a more conservative approach for the <u>alternate</u> FDS cable: **to increase the strength of the Model Design cable.** The outer strength member design readily provided the opportunity for an 18,000 lbs minimum break strength cable within a 0.500" overall diameter. This required only a minor increase in the steel cross-section. In Phase II, the cable did not require a complete redesign to increase the strength: the modification was a simple revision to the armor package, which did not alter the electro-optic core. The preliminary results in Phase II testing indicate that this program has been successful.

Rochester's attempt to prove that the Phase I alternate cable could be built with a Hytrel/Nylon jacketed fiber (vs. the steel tubed fiber) in the center of the copper stranding was inconclusive. The first 1 km length manufactured with AT&T's <u>hermetic</u> fiber suffered many optical fiber breaks. The 1 km replacement length incorporated AT&T's <u>standard</u> depressed clad fiber, which remained continuous throughout testing. However, this approach does <u>not</u> provide a hermetic barrier within the cable to insure the fiber's long term optical performance.

3.0 PHASE II ALTERNATE DEEP WATER TRUNK CABLE DEVELOPMENT

3.1 ALTERNATE CABLE PHASE II SPECIFICATION

The primary purpose of the Phase II ADWT development was to prove that at least two cable vendors could manufacture the cable in continuous lengths greater than or equal to 10 km. From the testing of Phase I cable, however, it was obvious that one could easily increase the strength and working load capability of an outer strength member cable, and still remain within a nominal 0.500" OD. Consequently, it was decided for reasons summarized below, that **the Phase II ADWT cable development should prove both long-length manufacturability and increased strength.**

The procurement and award of contracts to build Phase II cable is discussed in Section 3.2 below. In summary, three (3) contracts were awarded in August/September 1989 to three independent cable vendors:

(1) Consolidated Products Corp.--to build 15 km cable,
(2) Simplex Wire & Cable Co.--to build 15 km cable, and
(3) STC Submarine Cable Systems (England)--to build 8 km cable.

Consolidated Products built a continuous 15 km length of cable that passed final inspection on 14 Dec 89. STC-England completed the required 8 km continuous length and passed final inspection on 11 January 90. Neither CPC nor STC experienced major difficulties in building the required continuous lengths. Both companies had previously built Phase I cable prototypes, and both companies used existing machinery.

Simplex Wire & Cable was the only one of the three vendors unable to delivery their cable in a continuous length. They **delivered a 4.7 km length in January 90; and an additional 10.5 km length built to a modified design in mid-May 1990.** The reasons for loss of the originally attempted 15 km length are discussed below in Section 3.5. Simplex had not previously built cable of this type (they were not part of Alternate FDS Phase I).

3.1.1 Key Issue: Need for High-Strength Cable. Although the FDS "B1 Specification" as prepared by AT&T indicated that 5,000 lbs working load and 8,000 lbs minimum cable break strength were sufficient, there existed some concern as to whether these values continued to be applicable after the CSM/DWT cable diameter was increased from 0.372" to 0.450"; and finally, to 0.525" OD. As the cable design changed, the associated increases in cable in-water weight necessitated that the cable experience greater tension during deployment or recovery from a given ocean depth. The strength requirements in the B1 Spec were determined by calculation of the tensions expected in the 0.372"OD cable. Since the CSM cables continued to use the same center strength member design, which provided 5,000 lbs working load and 8,000 lbs min breaking strength, it is obvious that the larger cables with an increased in-water weight would experience a greater load under the same conditions.

The Phase II ADWT cable specification, "Specification for a Seafloor Electro-Opto-Mechanical Cable," Revision B, dated 7 March 1989, contained the cross-sectional drawing shown in Figure 11. As can be seen by the mechanical properties, a minimum break strength of 14,477 lbs was required, and a minimum working load of 8,000 lbs with $\leq$ 0.65% axial strain. After conducting studies on the deployment and recovery of DWT cable during April and May 1989, it was decided to increase the working load requirement from 8,000 to 9,000 lbs with $\leq$ 0.7% cable strain, and to demand a minimum cable break strength of 16,000 lbs. The increase in strength requirements were not formally incorporated into the Rev B Specification; however, a Memo from T. Stamnitz, SAIC to K. Rogers at NOSC (SAIC/TCS-013; 5 June 89) on this subject was sent to Western Instruments Corp.(WIC), NOSC's fiber optic cable development contractor, and eventually passed on to WIC's cable subcontractors. Both CPC and Simplex chose to respond to the request for increased strength and proposed cables with 9,000 lbs working load. STC-England proposed to meet the Rev B spec.

Tension testing of the cables manufactured by CPC and Simplex indicate that both companies met the requirement for 9,000 lbs working load and 16,000 lbs min break strength. STC-England's cable met the mechanical requirements of the Rev B spec. Thus, it can be stated that **all three vendors have proved that a high-strength DWT cable can be built in the outer strength member configuration, such that it demonstrates a <u>working load</u> capability which is equal to or greater than the <u>break strength</u> of AT&T's comparable center strength member cable.**

3.1.2 Manufacturing Methods and Concerns. In Phase II, Simplex proposed and built the electro-optic strand, using shaped-segmented copper conductors stranded around the steel-tubed fiber optic unit, in accordance with the design cross-section (Figure 11). SAIC and WIC sent representatives to Simplex to observe this fabrication. Although Simplex experienced some difficulty (Section 3.5 below) during the first run after 5.6 km, they were able to make minor adjustments to the setup and subsequently ran $\geq$ 10 km cable without a problem. It is believed that the fully shaped, segmented copper conductor is compatible with the OSM/steel tubed fiber design. Simplex's process uses a tandem setup with an in-line extruder, such that the completed copper stranded steel tube goes directly into extrusion to receive the polyethylene insulation. The process runs at relatively high line speeds, and allows complete cable fabrication with only three processes: (1) stranding + extrusion, (2) armoring, and (3) outer jacketing. While the shaped, segmented copper conductor is the most efficient way of obtaining the required electrical conductivity <u>within the smallest diameter</u>, not all cable companies have the capability of performing this process.

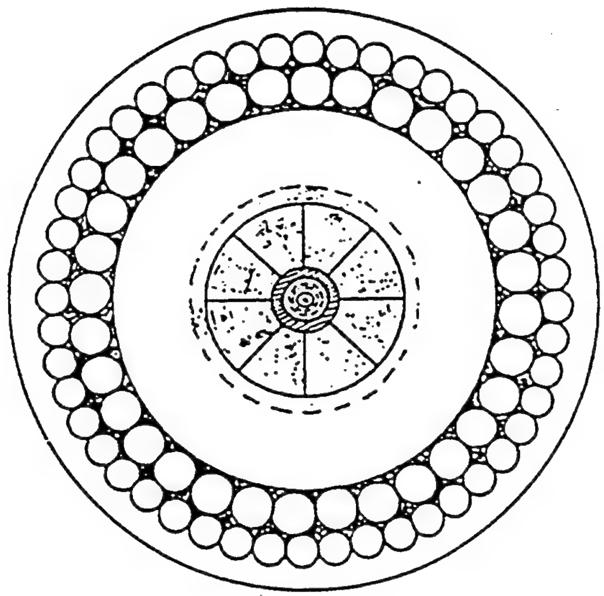
During Phase I prototype fabrication, STC-England experienced some difficulty in obtaining good preform in the outer layer of armor wires, and in obtaining a quality, uniformly thick jacket extrusion thereover. Consequently, in Phase II they proposed using 40 (vs. 48) wires with increased diameter in the outer layer, and in

COMPOSITE E-O CONDUCTOR:
Single Mode Fiber
8/125 Glass....... 0.005"
UV-acrylate....... 0.010"
Steel Alloy Tube
Void-fil gel...... 0.027"
Laser welded OD... 0.032"
Shaped Copper Strand
> #7 AWG compacted 0.160"

2) INSULATION STRUCTURE:
MDPE dielectric..0.284"
(with EAA copolymer)

3) DOUBLE-STEEL ARMOR:
24/0.040" GXIPS..0.364" (16.5°)
40/0.028" GXIPS..0.420" (17.0°)

4) OUTER HDPE JKT
0.500, +0.010/-0.000"



ELECTRICAL PROPERTIES:
DC Resistance ≤ 1.5 ohms/km
Rated Voltage = 4,000 Vdc nom

OPTICAL PROPERTIES:
Atten(1300nm) ≤ 0.50 dB/km
Atten(1550nm) ≤ 0.30 dB/km
Disp'n (1300) ≤ 2.5 ps/nm-km
Disp'n (1550) ≤ 16.5 ps/nm-km

MECHANICAL PROPERTIES:
Break Strength (min) = 14,477 lb_f
Work Load = 8,000 lb_f min
Elongation (max @ WL) = 0.65%
Torque @ WL ≤ 24 in-lb_f
Rotation @ WL ≤ 1.2 deg/ft

PHYSICAL PROPERTIES:
OD = 0.500" ± 0.010
Weight in air ≤ 305 lb_f/kft

Figure 11. NOSC's Alternate DWT Phase II Model Design

addition a thicker HDPE jacket extrusion--resulting in an 0.525"OD cable (vs. the Phase I cable 0.47" OD). In this way, STC was able to provide a uniformly armored and jacketed 8 km length without any reported difficulties.

Consolidated Products Corp used three layers of relatively small copper wires (0.025" OD ea.) to form the stranded conductor during Phase I. Although this approach tested very well, CPC indicated that the production speeds were slow, requiring two passes through the processing line (one pass for the first two layers and a second pass for the third layer). CPC proposed a modified copper stranding design for Phase II, which used only two layers with seven conductors each. The two layers were laid simultaneously at a greater line rate, and Phase II electrical testing indicates that the results were successful. Thus, CPC's Phase II effort proves that long-continuous lengths of OSM/DWT cable can be made using conventional round-wire copper stranding around the steel tube. This is considered an important result, because nearly every cable plant in the world can strand round, bare copper wire.

3.2 PHASE II ALTERNATE CABLE PROCUREMENT AND AWARDS

The Phase II cable design, as contained in NOSC's previously referenced Rev B Spec, and the corresponding Statement of Work were completed by engineering personnel at SAIC and NOSC by mid-March 1989. A delivery order was awarded in June 1989 to Western Instrument Corporation (WIC). WIC issued an RFQ to prospective cable vendors in early July, which resulted in the receipt of four proposals from cable suppliers by 11 July 1990. These proposals were reviewed by Lee Tucker, Senior Electrical Engineer, WIC, and T. Stamnitz, Senior Physicist for Fiber-Optic Cable Systems, SAIC, the following week. Proposals were received from: (1) Consolidated Products Corp, (2) Simplex Wire & Cable Co., (3) STC-England, and (4) The Rochester Corp.

The prospective cable suppliers included estimated selling costs for their proposed cable designs, for production ($\geq$1,000 Nmi) quantities. The estimated costs were provided to the Navy as "proprietary" information, and have consequently been documented to the FDS Program Office under separate cover.

The proposals from Simplex, Consolidated Products, and STC for fabrication of Phase II cable were evaluated as being technically acceptable; consequently, Simplex and CPC were awarded contracts in early August 1989 based upon being the lowest bidders. TRC was considered non-responsive, since they proposed building Phase I cable, which definitely could not meet the high-strength Phase II, Rev B Specification.

The total cost of the two contracts at Simplex and CPC was sufficiently below the budgeted amount that it was possible to award an additional contract to STC-England in early September 1989; but for an 8 km length of cable only. Added impetus to award the 8 km contract to STC came from the Technology Demonstration System project at NOSC, which required a "shore landing cable"

containing three optical fibers. This explains why the STC Phase II cable contained three optical fibers versus the one fiber optic required in the Rev B Specification. With the exception of including three optical fibers in the central steel tube, the STC cable was built in accordance with the Rev B Spec. The design and manufacturing of the three cables built for Phase II by the three respective vendors will now be discussed.

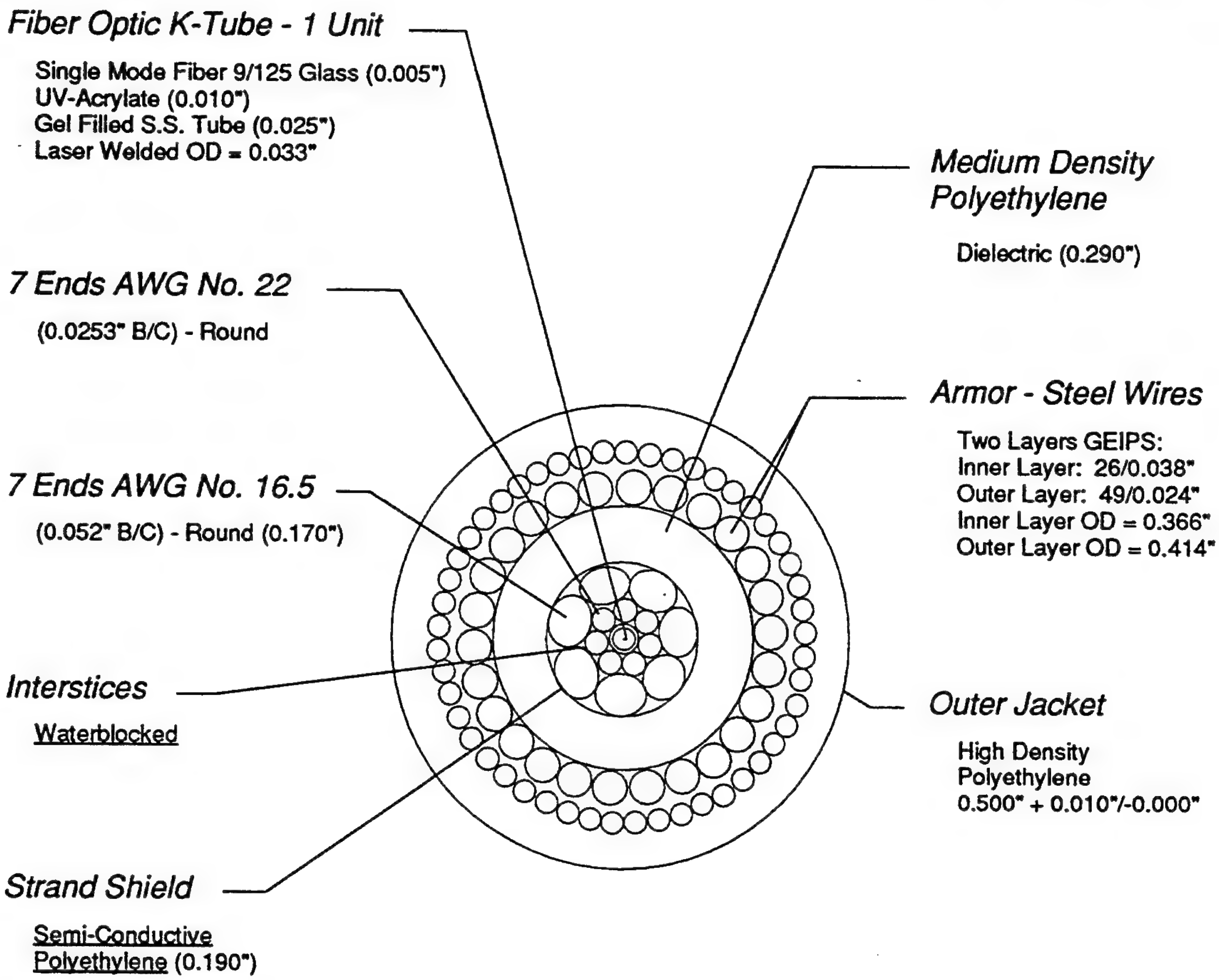
3.3 CONSOLIDATED PRODUCTS CORP: SB-38262 SEAFLOOR EOM CABLE

The Phase II cable design, SB-38262, as proposed and contracted for manufacture in a 15 km length by Consolidated Products Corp., is shown in Figure 12. This cable was manufactured during an eight week period beginning in mid-October 89 and ending with the Final Inspection on 14 December 89. The two-layered copper conductor stranding was fabricated at the plant in Idyllwild, CA, whereas the remaining three processes (insulation extrusion, armoring, and jacketing) were performed at their larger plant in Temecula, CA. The completed cable was measured optically to be 14.5 km in length. All electrical, optical, and mechanical Final Inspection requirements were passed. CPC shipped the cable directly to NOSC.

The most interesting aspects of the CPC design, i.e. the copper stranding and the double-steel armor package, will be discussed in detail below. As mentioned above, CPC chose to build a cable in accordance with the "high-strength" request for 9,000 lbs working load and 16,000 lbs minimum break strength. Test results indicate that these mechanical performance goals were met, and that the optical fiber attention was 0.35 Db/km at 1.31 microns, and 0.23 Db/km at 1.55 microns. These values in the completed cable were slightly better than the values measured at Laser ArmorTech prior to encasing the optical fiber into the small-diameter stainless steel tube. Further, these values have remained essentially constant throughout an extensive test program conducted at NOSC and Tension Member Technology. The detailed test results are the subject of a separate report.

In comparing the three Phase II cable vendors in general, it may be stated that Consolidated Products was the company most able to respond expeditiously to the long-length manufacturing requirement. They were the only company able to delivery prior to the end of calendar year 1989--the original delivery goal. From the standpoint of performance, preliminary test data shows that they met the "high-strength" requirement, and obtained extremely low loss in the optical fiber. (Although Simplex had a stronger cable, they were unable to deliver a continuous 15 km length--see Section 3.5 below). The double-steel armoring line used by CPC was optimum in size and performance for the task of armoring Phase II cable, while both Simplex and STC utilized much larger, heavier, and more costly armoring lines. The reason for this difference is that the armor lines used by Simplex and STC were previously designed to armor much larger transoceanic cables, using much heavier gauged armor wires than required for the Phase II ADWT armor package. The CPC armoring line is sized perfectly for the task of production runs on Phase II cable. If the requirement for production of Phase II cable arises in the future, CPC stated that they could make such an armoring line available on a dedicated basis. The cost of setting up such a dedicated line was not discussed.

Consolidated Phase II



Electrical Properties

DC Resistance ≤ 1.5 ohms/km
Rated Voltage = 4,000 VDC Nominal

Optical Properties

Attenuation (1300 nm) ≤ 0.50 dB/km
Attenuation (1550 nm) ≤ 0.30 dB/km
Disp'n (1300) ≤ 2.5 ps/nm - km
Disp'n (1550) ≤ 16.5 ps/nm - km

Physical Properties

OD = 0.500" + 0.010" - 0.00"
Weight in air ≤ 305 lbs/kft

Mechanical Properties

Min. Breaking Strength = 16,000 lbs
Working Load = 9,000 lbs
Max Elongation @ W.L. = 0.7%
Torque @ W.L. ≤ 24 in.-lb.
Rotation @ W.L. ≤ 1.2 deg/ft

Figure 12. Consolidated Products: Phase II Alternate DWT

3.3.1 Improved Electro-Optic Strand. As summarized in the closing paragraph of Section 3.1.2 above, CPC proposed and built during Phase II an electro-optic strand that used two layers of round copper wire stranded about the 0.033"OD laser welded stainless steel tube containing the optical fiber. This strand represents a significant improvement over their Phase I cable strand from the standpoint of manufacturing. The latter required two processing steps to strand three layers of wire, whereas in Phase II only one processing step was needed to strand the two layer design. The two layer configuration is a left-hand (LH) "unilay" construction employing seven (7) ends of #22 AWG (American Wire Gauge) bare copper (0.0253" diameter each) in the inner layer, and seven (7) ends of #16-1/2 AWG bare copper (0.052" diameter each) in the outer layer. The strainer plate is arranged to cause the larger outer layer wires to settle into the outermost interstices of the smaller inner layer wires, as can be seen on the cross-sectional drawing. The outer diameter (OD) over the electro-optic strand is 0.170" by design, and 0.171" OD was actually measured on the completed cable.

The proposed 2.75" LH lay-length (LL) produces a 3.8 deg LH lay-angle (helix angle) in the inner layer wires, and 7.7 deg LH lay-angle in the outer layer wires. A 30 ft/min (FPM) line speed requires about 130 RPM's (revolutions per minute) from the copper strand machine. Although this rate is relatively slow, it is faster than the 20 FPM rate realized in fabricating the WI-08 CSM cable on the IC-line at Simplex. The copper stranding operation at CPC is extremely low risk, however, and uses conventional low-technology machines. Once the operation began, there were no events that required stopping the process.

The SB-38262 cable also employed a semi-conductive polyethylene strand shield over the electro-optic strand, extruded to 0.190" OD. This shield was used to reduce the voltage stress at the conductor/insulation interface to about 75 volts/mil under the application of 4,000 Vdc. Both CPC and STC used such a strand shield on their Phase I cable prototypes; however, CPC was the only company that retained this feature in Phase II. It appears now, based upon the absence of corona inception during the testing of several ADWT cables <u>without</u> the strand shield, that it is not required. While the strand shield reduces voltage stress and likely increases the cables insulation life, it appears that the 25 year life requirement can be met without a strand shield. CPC indicated that they would be happy to eliminate the strand shield on future cables, and that a corresponding price decrease would result.

3.3.2 Torque-Balanced Armor Without Preform. The torque-balanced steel armor design proposed and built by CPC during Phase II demonstrated $\geq$ 16,000 lbs break strength; also, the cable experienced $\leq$ 0.7% axial strain at 9,000 lbs while generating $\leq$ 5 in-lbs total torque at this working load. While these performance values are extremely impressive, one puzzling feature of CPC's design from the manufacturing standpoint will now be described.

First, one should compare the double-steel armor design used in the Phase I "model design" cable (Figure 6) with that used in the Phase II model design (Figure 11). Note that the Phase I model design employed 28 wires (0.032" OD ea) in the first layer, and 46 wires (0.023" OD ea) in the second layer. The cable overall diameter constraint of ≤ 0.500 inches resulted in a design using a relatively large number of fairly fine gauge wires. In practice during Phase I, STC followed this approach closely and experienced some difficulty getting a good "preform" in the outer layer wires. The possibility of achieving good preform is a function of the wire size, the pitch-diameter of the wire's helical path, and the lay-angle of the helix. To improve the possibility of achieving good preform during Phase II, the model design was modified to include a smaller number of slightly larger wires: 24 wires (0.040" OD ea) in the first lay, and 40 wires (0.028" OD ea) in the second lay. The Phase II design also provided an increased total cross-section of steel (compared to Phase I design) in order to increase the nominal break strength from 12,000 lbs to about 14,500 lbs.

CPC's Phase I cable (Figure 8) did not follow the Phase I model design with respect to the outer armor layer; in fact, CPC used a "spaced" outer layer comprised of 24 x 0.031" OD wires. Since the 0.031" OD wire is easier to preform, as compared to the 0.023" OD wire proposed for the outer layer Phase I model design, CPC did not experience any difficulty obtaining preform in Phase I.

Based upon the Phase II model design, it was expected that all vendors would propose using a relatively smaller number of larger wires in their Phase II designs. However, in the case of CPC, exactly the opposite occurred. Instead of 40 x 0.028" OD wires, CPC proposed 49 x 0.024" OD wires! After contract award, during the "design review" discussions preceding fabrication, the Navy expressed to CPC the concern that it would not be possible to obtain good preform with so many small wires in the outer lay. To our surprise, CPC responded that they had no intention of applying preform at all. Their concept of the SB-38262 cable manufacturing included armoring both layers in a single-pass, but with no preform heads in-line to pre-shape the wire helix prior to passing through the closing die for positioning about the cable core. CPC stated that they had developed this technique by building an "in-house" prototype of SB-38262 using their own funds, and that they were able to control the wire positioning sufficiently well to preclude the need for preform. They provided the Navy with a sample of the prototype cable, demonstrating that such an approach was indeed possible. Elimination of armor preform was viewed as one more step in the direction of simplification, which provided in addition the advantage of not stripping off any of the zinc coating over the steel wire during fabrication. CPC claimed that the armor line speed could be increased by eliminating preform heads.

In retrospect, it appears that initial concerns with respect to using 49 x 0.024" OD wires were justified. Although CPC was able to fabricate the steel armor package without any detrimental incidents, problems arose afterwards during the respool operation to prepare the cable for outer jacketing extrusion. Because the

armor wire was not preformed, there was a tendency for the wires to snarl and tangle whenever tension was lost during the respool. In other words, the lack of preform caused handling problems prior to encapsulating the armored cable within the outer HDPE jacketing extrusion. Once the outer jacket was in place, the cable appeared to be well-behaved. Before jacketing, however, CPC lost about 1.5 km of cable, which resulted in a 14.5 km completed length versus the 16+ km length that would have resulted otherwise. CPC stated later that in view of this problem, which increased the degree of difficulty and risk prior to outer jacketing, they would propose using a smaller number of larger wires in the outer layer in the future.

3.3.3 Manufacturing Issues. The primary manufacturing issue with respect to CPC's cable was the one addressed in the preceding paragraphs, i.e. the apparent need to apply preform to the armor wires to reduce the risk of loss prior to outer cable jacketing. This can be achieved, as stated above, by using a smaller number of larger wires in the second steel wire layer.

CPC's use of the spaced outer armor layer in their Phase I design (24 x 0.031" OD ea), wherein the wire experienced a permanent helical set by passing through the preform heads, suggests an interesting option--the possibility of armoring future OSM/ADWT cables with a tubular strander. The primary drawback in CPC's Phase I approach was their inability to obtain uniform spacing of the wires. The principle advantage was the use of a relatively small number (24) of wires in the second layer, because **the use of ≤ 24 wires in both the inner and outer layers opens the door to the possibility of using a tubular strander as the armoring machine.**

All of the OSM alternate DWT cables to date have been built using conventional planetary cabling machines to serve the steel wire into the armoring line. The drawback of an armoring line which uses planetary stranders is the relatively slow line speed (about 50 FPM max), while the advantage is high-reliability and low risk. It is possible that an OSM cable could be designed for fabrication on a tubular stranding line, which could have a line speed of over 400 FPM! In order to obtain uniform spacing of the wires (say 24 x 0.031" OD), however, it would likely be necessary to individually jacket each of the steel wires prior to loading onto the tubular stranders payoffs. Jacketing of the steel wires with HDPE, for example, could conceivably be done on a small inexpensive extruder at a line speed of several hundred FPM. Consequently, the tradeoff consists of evaluating the use of two high-speed operations (wire jacket extrusion + tubular stranding) in place of one slower operation (planetary armoring).

3.3.4 Ability to Support Volume Production. It is worth noting that CPC has an ideal manufacturing facility for producing volume quantities of the OSM/steel tubed fiber cable. The floor space available in their new Rancho California Plant (about 3 years old) would be sufficient to support a "dedicated" facility for OSM alternate DWT cable. CPC's technical and price proposal for the Phase II cable contract contained an extensive description of their

facilities; including equipment types, capacities, and plans for the future. The machinery used to fabricate the 15 km Phase II cable included: (1) the bunching machine for copper stranding of the steel tube, (2) the extrusion line for electrically insulating the electro-optic strand and applying the outer cable jacket, and (3) the planetary double-steel armoring line. All presently have capacity ratings sufficient to build up to 50 km continuous lengths of the OSM/ADWT cable. CPC also quoted a 28 month maximum delivery time for a 1,000 Nmi order--which corresponds to an existing capacity of about 65 km/month (approximately ~35 Nmi/month). This capacity is available now without any equipment investment or facilities expansion. In fact, CPC stated that the Rancho California Plant is presently used at only 20% capacity; therefore, they are seeking work of the OSM/ADWT cable type to fill the plant.

Consolidated Products' quote also indicated that they could easily expand the Rancho California Plant's capacity to produce 150-200 km/month of OSM/ADWT cable by installing an additional copper bunching line and an additional planetary tandem armoring line (no additional extrusion equipment is required). Both of the new lines would be clones of the lines used to build the Phase II cable, which were designed and built by CPC in their own machine shop. The cost of these lines, which is estimated at $500-750k, would be borne by Consolidated Products in the event of an order for 2,000 to 3,000 Nmi of ADWT cable. They estimate that about 12 months would be required ARO to bring the new equipment on-line.

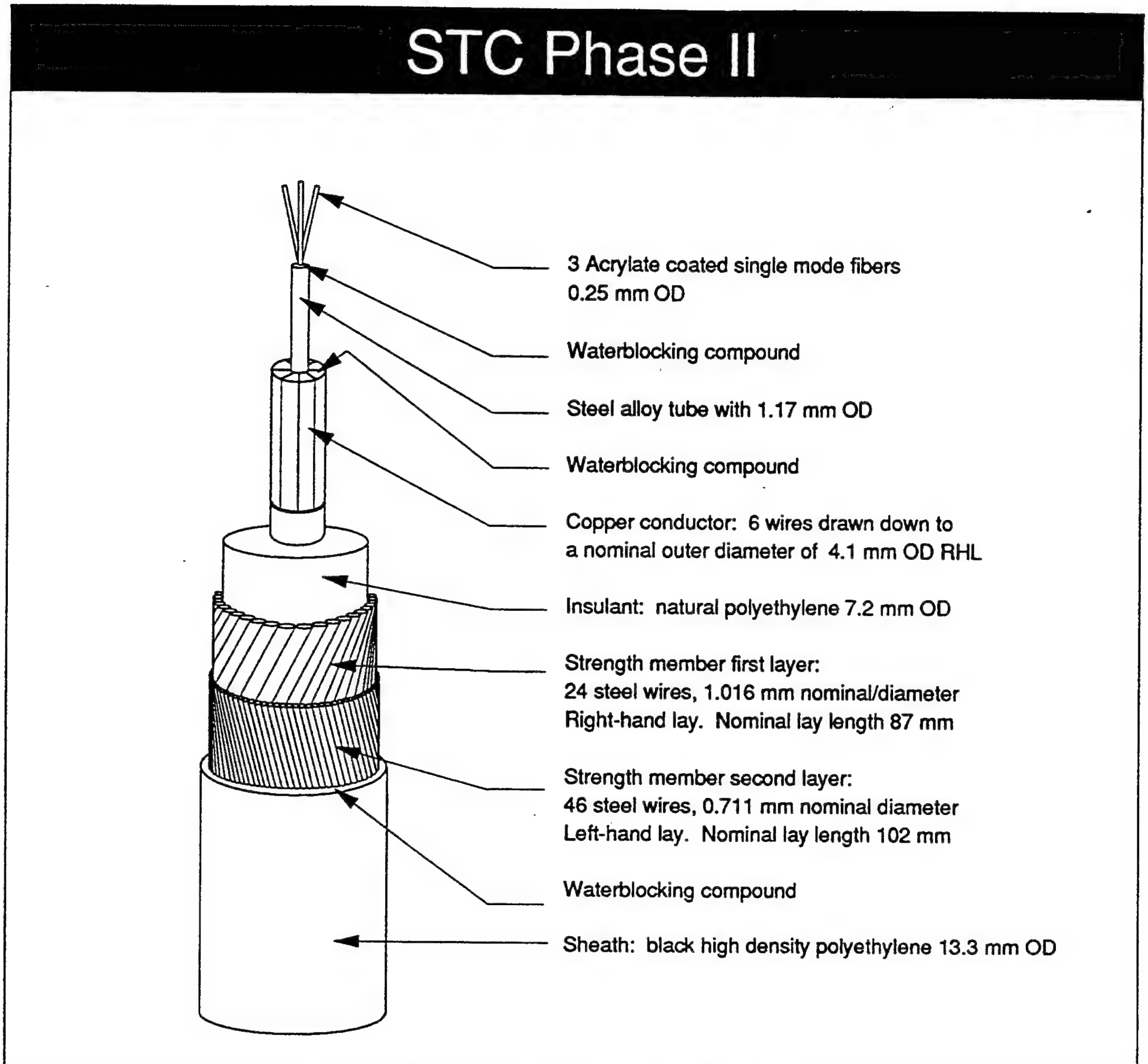
The Rancho California Plant is located about one hour's distance from ports in Long Beach, CA that can support loading of ocean-going cable-laying ships. Earlier studies suggest that about 35 Nmi (70 km) of OSM cable with diameter $\leq$ 0.500" could be shipped by truck on steel cable reels. The cost of this shipment, and loading on a cable ship in Long Beach has not been investigated.

3.4 STC SUBMARINE CABLE SYSTEMS: SEAFLOOR EOM CABLE

The manufacture of an 8 km Phase II ADWT cable was completed and inspected on 11 January 1990 at the STC Cable Products Division, Newport, Wales. The plan view of the STC cable is shown in Figure 13, and photocopy of two photographs of the actual cable cross-section as taken by STC is shown in Figure 14. The STC cable was built in accordance with NOSC's "Seafloor EOM Cable Specification," Revision B, dated 7 March 1989 (see Figure 11). The only significant deviation from the "model design" was the use of three optical fibers encased in an 0.046" OD stainless steel tube (versus one optical fiber in an 0.033" OD tube). The STC contract was based upon employing the 3-fiber steel tube at the request of NOSC, since the STC cable will be used by the Technology Demonstration System (TDS) as an 8 km shore landing cable. (As a result of the intended use, the completed 8 km length is presently receiving additional heavy armoring under a separate contract, and will be deployed in August - September 1990).

STC did not encounter any difficulties in producing the 8 km length. Furthermore, STC stated that they could easily have produced 20-25 km on the same manufacturing equipment. Manufacture of the 8 km cable was under the direction of STC Submarine Systems personnel from Southampton, England, namely Dr. Stuart R. Barnes, Technical Director, and Chris Rochester, Cable Engineer. Dr. Peter G. Hale, Special Projects, CPD Newport, Wales, directed the actual manufacturing and development effort. STC conducted a complete set of in-house tests that surpassed those required by the contract, partially motivated (it appears) by their interest in evaluating this type of cable for their own commercial use. Much of this testing was done under the direction of Dr. John Lees, Technical Director at STL (STC Technology Ltd), Harlow, Essex, England.

As evidence of STC's commitment, they also generated a detailed "Report on Manufacture of A Seafloor Electro-Opto-Mechanical Cable For Western Instruments," by Brian A. Eales (Cable and Material Engineering Department, Materials and Processing Report No. 423/102, STC Technology Limited, 31 January 1990). This report covers the manufacture of a "preproduction prototype," a non-deliverable under their contract, for the purpose of evaluating manufacturing processes in advance of producing the 8km deliverable. It also discusses the cable design features, the quality assurance and testing, and reports on dynamic tensile testing of two distinct steel tubed fiber optic elements; one from Laser ArmorTech (San Diego, CA) and one from Helios, Inc. (Tokyo, Japan). Finally, they attached a complete set of test data, including all of the OTDR traces made during each phase of the cable manufacturing process. Some of the information presented below has been taken from the STC Manufacturing Report.

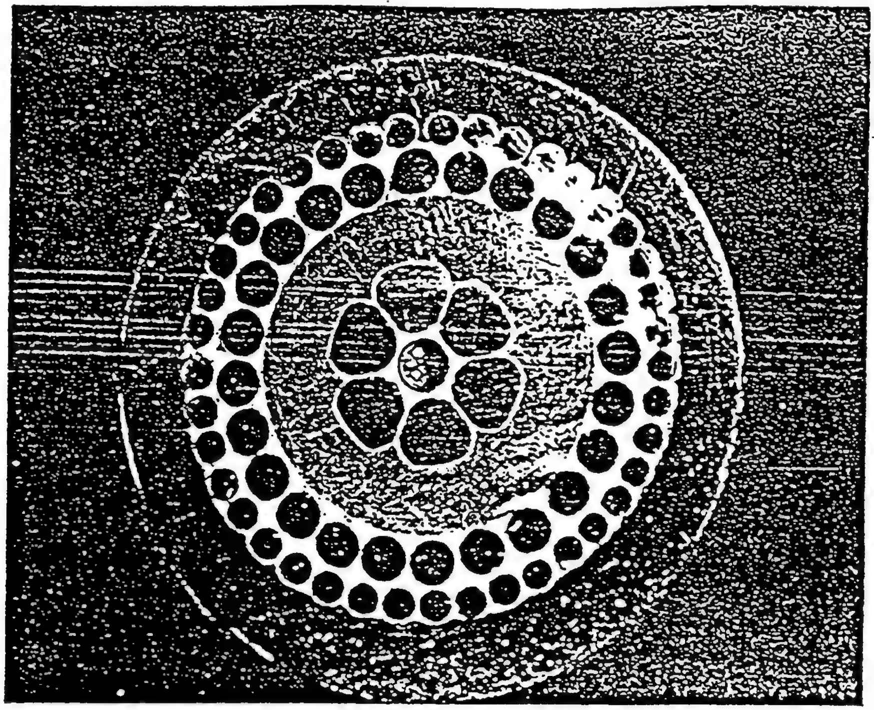


Nominal Physical Characteristics of Cable

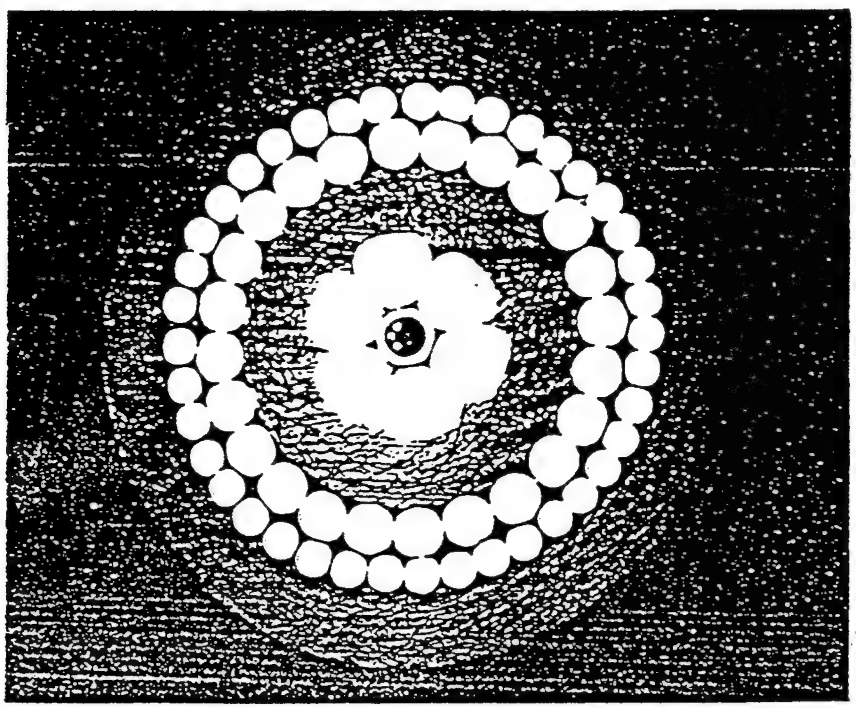
Seafloor Electro-Opto-Mechanical cable

Sheath outer diameter	13.3 mm
Total cable weight in air	0.486 kg/m
Total cable weight in water	0.344 kg/m
Specific gravity	3.50
Stowage factor	0.17 m^2/km
Minimum U.T.S.	66 kN
Nominal Tensile Stiffness	7.4 MN
Hydrodynamic constant	0.56 Rad m/s
Minimum bend dia. (Finished Cable)	1.0 m
Minimum Load at 1% strain	54 kN
Composite Power Feed Conductor Resistance	<1.5 ohm km @ 20° C
Insulation Resistance	>3.5 x 10^9 ohm km
Composite Power Feed Conductor Capacitance	0.298 μf/km

Figure 13. Illustration of STC Phase II Design



Oblique incidence illumination



Coaxial illumination

Figure 14. Cross-Section of STC's Delivered Cable

The STC cable displayed excellent optical loss characteristics: 0.34 dB/km at 1310 nm and 0.20 Db/km at 1550 nm are nominal values, which are essentially the same optical loss values measured at Laser ArmorTech after encapsulation of the three optical fibers into the stainless steel tube.

3.4.1 Electro-Optic Strand With Three Optical Fibers. As can be seen in Figure 13, the STC cable employed three (3) single mode optical fibers in the 0.046" OD (1.17 mm) stainless steel tube. This armored optical element was fabricated by Laser ArmorTech (formerly K-Tube Corp) in San Diego, CA. This tube is 0.013 inches larger in diameter than the single fiber/steel tube used by STC to build a 1.5 km Phase I ADWT prototype. The larger diameter steel tube turned out to be an advantage for STC from the cable design point of view, because the partially shaped copper stranding design used by STC results in a central "inner hole" that is about 0.045" in diameter. In Phase I, the smaller steel tube did not fully occupy the space available, hence, the steel tube was loose within the electro-optic strand construction. The electro-optic strand in the Phase II cable, which used the larger steel tube, demonstrated integral mechanical contact of the copper wires about the steel tube. This is believed to be a positive design feature, since it ensures that the steel tubed fiber element will follow the surrounding cable structure to experience axial strain under cable loading.

The copper strand about the steel tube was formed from six #16 SWG, soft electrical grade copper wires, which were wrapped at about 3.3 lbf tension about the steel tube using an Edmands Strander. The strander appeared to be a new machine, in excellent condition, which ran very smoothly at 200 RPM, corresponding to a line speed of 60 FPM due to the 3.6" lay-length (left-hand direction). This rate equals about 1 km of production every three hours; thus the total run time for 8 km is about 24 hours. For comparison, the stranding rate is about three (3) times faster than the IC-Line stranding of the CSM cable at Simplex.

The completed electro-optic strand was drawn through a closing die at the exit of the stranding machine, which partially deformed the round copper wire into "bean shaped" conductors, with a final dimension of 0.165 inches. This partial compaction of the relatively large round wires provides better space efficiency. Although this approach is not quite as space efficient as the shaped copper strand produced by Simplex (see Section 3.5.1), there are several advantages. For example, the availability of intersticial space on the outside of the completed package between the adjacent copper wires, provides "footings" for pressure extrusion of the subsequent MDPE insulation. In effect, the insulation is forced into the outer intersticial space under high pressure, and upon curing to a hard plastic, it mechanically grips the electro-optic strand. This insures shear transfer. The Consolidated Products design also has this advantage.

The inside intersticial spaces between adjacent copper wires were filled with a Room Temperature Vulcanizing (RTV) silicone rubber material in-line with the stranding. A hot air preheat system was used to accelerate the cure of the RTV silicone waterblock compound to prevent successive layers of completed strand from adhering to each other on the take-up drum. The in-house preproduction prototype effort was conducted to determine specific process parameters, and during the fabrication of this 800 m length the flow of RTV silicone was excessive. Consequently, STC was forced to remove the excess RTV by hand during an unscheduled respool operation. The important thing to note is that STC's product was a truly waterblocked strand.

For the 8 km production run the flow of RTV was controlled, but the excess was not totally eliminated. For this reason, STC devised two pairs of opposed motorized rotating steel brushes; one pair mounted vertically and the other pair horizontally. This procedure was successful in removing excess RTV at 1200 m per hour line speed, although some small amount of RTV remained in the bottom of the helical depression occasionally. The brushing procedure also engendered some waviness in certain sections of the core length.

The subsequent MDPE extrusion was carried out at 105 FPM (nearly 2,000 meters per hour). No on-line degreaser was used, but conductor preheat by induction heating was used prior to entry into the extruder cross-head. The concentricity of the conductor and the outside surface of the insulation was very uniform. One large lump occurred in the MDPE insulation at 3773 meters from the top end of the completed core. This lump was removed by sanding during the armoring operation.

3.4.2 Torque-Balanced Steel Armor Construction. The double steel wire strength member package was fabricated in one pass through a dual armoring machine. The armor machine was made by Northampton Machinery Co., and contained 96 bobbins total--i.e., a maximum of 48 wires could be applied in one layer. The actual armor construction as manufactured consisted of:

1st Lay RH: 24-ends 0.040"GXIPS, 3.58"LL, 15.8^, 98.6%, 0.362"OD
2nd Lay LH: 40-ends 0.028"GXIPS, 4.02"LL, 17.0^, 95.4%, 0.419"OD

This armoring machine appeared to be somewhat large for the size of wires being applied to the cable, and in addition, only one-half of the available pay-offs were used in the first layer. It is believed that this line would typically be used to strand heavier gauge wire onto relatively large diameter cables ($\geq$ 1.00 inches). However, the armored cable product appeared uniform and of good quality. The armor line was equipped with a good set of wire preform heads in front of the closing dies for both the first and second layers. The wires took a permanent set and the measured preform for the inner layer was 76%; while the outer layer measured 80%. This compares favorably to the 78 $\pm$ 3% required in the Rev B spec.

STC designed and installed special tooling to enable flooding application of RTV silicone waterblock material at the closing die of the inner armor strand. A PTFE plate with an aperture of 0.375" was used in series this arrangement to redistribute excess silicone RTV around the periphery of the inner strand in order to achieve blocking between the inner and outer armor strand. After fabricating preproduction cable in this way, subsequent water tightness testing indicated the method was inadequate, with some seepage observed between the inner and outer layer strand. A further stage of RTV silicone injection was installed for the deliverable cable fabrication, which provided a film about 0.010" thick of RTV on the outer surface of the inner armor strand wire, into which the outer strands were embedded. This method proved successful.

STC was forced to make four welds, one in each of four wires in the outer layer, due to having received several short lengths from their steel wire supplier. The capacity of the bobbins was greater than the approximately 9 km continuous wire needed to produce the 8 km cable; however, they did not receive 40 continuous lengths in excess of 9 km. The four welds were installed at 265 ft, 1325 ft, 1585 ft and 2,900 ft from the top end of the completed armored cable. The operators making these welds were fully certified via 10 practice welds. This is standard practice in the cable industry, and in view of the outer extruded HDPE jacket over the armor, such welds are not expected to cause any problems during cable installation or recovery.

3.4.3 **Manufacturing Issues.** The armor stranding was carried out at a line speed of 10 FPM, which is slow when compared to the IC-Line at Simplex--which produces CSM/DWT cable at about 20 FPM. The advantage of the STC armor process in comparison, however, is that this type of planetary armoring process has been used in the cable industry for at least 50 years. It is a low technology and low risk process. Since the armoring machinery at STC is extremely large and heavy, it has an estimated value in the range of $1 million dollars. However, this is about an order of magnitude less expensive then the cost of setting up an IC-Line to make the CSM cable. Consequently, STC could support a faster production operation by placing two dual armoring lines in parallel, so that twice as much cable could be armored simultaneously. A more obvious method for reducing costs would be to use a smaller planetary armoring line, as done at Consolidated Products, which could also run at higher RPM's due to decreased angular momentum. This objective should be included in STC's plans for facilitization at the new Portland facility.

3.4.4 **Ability to Support Volume Production.** The most important thing to understand is that at this time STC does **not** have the capability to produce the Phase II type OSM cable in the United States. STC stated that the machinery used to build the 8 km Phase II cable in England could be used to build a 25 km length without modification. However, the main disadvantage for STC is the fact that the cable produced is likely to have an application in the Pacific Ocean. As shown earlier in Table 2 (Section 3.2), STC's

price per km for Phase II cable was greater than any of the other bidders. When the cost of shipping the cable across the Atlantic Ocean and across the continent of the United States is taken into account--things begin to look worse.

STC's new plant in Portland, Oregon opened about one year ago. At the present time the manufacturing line has been custom designed as a clone of a line in Southampton that can only be used to fabricate STC's "NL cable," a relatively large diameter commercial deep water trunk. It is hoped that the Portland Plant will eventually obtain the ability to make the Phase II ADWT type cable as made at the plant in Newport, Wales. However, STC Portland must obtain financial support from STC Headquarters in Greenwich, England, in order to undergo facilitization needed to build Phase II cable. At the time of this writing, the Portland Division had not yet obtained a firm commitment from England.

The reason for lack of commitment to the outer strength member cable fabrication is likely related to STC's recent commitment to the FDS Program Office to obtain facilitization in order to be able to build the CSM cable to the SPAWAR specification, which consists of the AT&T/Simplex 0.525" OD center strength member cable design. Informal reports from STC state that they have committed to an approximate $10 million dollar investment at Portland in order to support CSM cable fabrication. This investment cost is about ten times the investment that would be needed to produce the outer strength member Phase II type cable. However, it is likely that some of the equipment on order, in particular the armoring line, could support armoring of Phase II outer strength member cable. Thus, depending upon the configuration of the manufacturing setup, and the volume of CSM cable orders received, it is possible that STC Portland could use some of their new equipment to support OSM cable fabrication in the future.

In summary, STC's future with respect to volume production of OSM Phase II ADWT cable is an open question. Furthermore, they have not provided any written estimates of the projected cable selling price in the event of volume production. The Portland facility has not provided any indication of a projected selling cost of OSM Phase II cable in the event they obtain the capability to fabricate such a cable. This is all the more disconcerting in that STC initially demonstrated great interest in OSM cable, and has conducted the most conscientious program of in-house manufacturing trials and preproduction prototype testing.

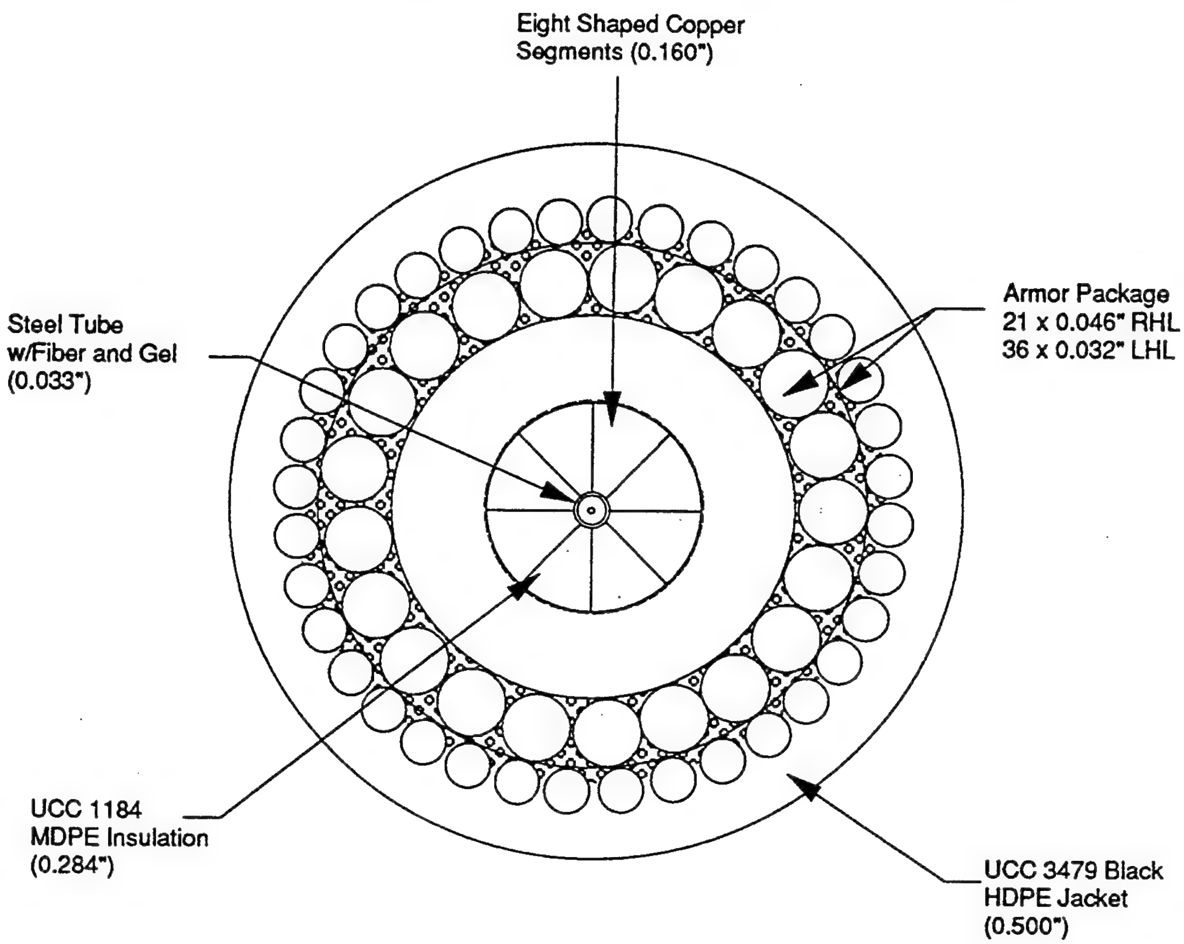
3.5 SIMPLEX WIRE & CABLE: SEAFLOOR EOM CABLE DEVELOPMENT

Simplex Wire & Cable did not participate in the Phase I ADWT cable development. In the summer of 1988 when Western Instruments Corp. conducted procurement of three 1 km cable lengths for Phase I, both Western Instruments and the Navy believed that Simplex would **not** be interested in the **outer strength member** cable approach, because they had previously declined to bid on several recent solicitations, and because they were AT&T's sole vendor for production of **center strength member** deep water trunk cable--both for SL cable for commercial systems and for development of the FDS Programs' center strength member DWT cable. In spring 1989 it was discovered that this assumption was totally incorrect.

When Simplex became aware of the significant results achieved in the Phase I ADWT cable development, they began to pay regular visits to Naval Ocean Systems Center, Advanced Applications Branch (Code 714). These meetings culminated in a high-level meeting at NOSC in March 1989, attended by John McIntyre, President, Simplex Wire & Cable. Mr. McIntyre convinced NOSC personnel that Simplex was extremely interested in participating and developing an outer strength member cable. Further, Mr. McIntyre made it very clear that Simplex was aware of the potential of using the small-diameter steel tubed fiber optic component as the central element in an outer strength member cable. He stated that Simplex was the premier long-haul deep water trunk cable supplier in the USA, and that they intended keep this reputation. Simplex's long range plans, in Mr. McIntyre's words, included the objective of becoming a supplier of OSM DWT type cable in the future. In fact, he said that the potential of such an approach appeared so imminent, that he 'had trouble sleeping at night' knowing that they were not yet involved in the development. Mr. McIntyre considered the steel-tubed fiber optic element as made by Laser ArmorTech as "a key factor that weighs on the conscience of the long-haul undersea cable community to keep us all honest."

Mr. McIntyre's words were backed up in July 1989 by a technical and price proposal to WIC, submitted by Simplex to support NOSC's Phase II OSM cable development. Actually, Simplex submitted three design options, and their proposal was given the highest rating during the contract evaluation. The Simplex technical proposal demonstrated a thorough investigation of design tradeoffs, manufacturing implications, and future implications for volume production. Consequently, they obtained a contract to build 15 km continuous cable on a best effort basis. The Simplex cable cross-section, as proposed, is shown in Figure 15. Since Simplex had not previously built this type of cable, and since they proposed to build the electro-optic strand using shaped, segmented copper conductors as shown in NOSC's Rev. B model design, they appeared somewhat at a disadvantage as compared to the other contractors, both of whom had built not only the 1 km Phase I deliverable but also significant in-house preproduction prototypes. It was believed by the Navy that the shaped, segmented copper construction represented the greatest

Simplex Phase II



Electrical Properties

DC Resistance ≤ 1.5 ohms/km
4,000 VDC without corona

Optical Properties

Atten @ 1310 nm 0.50 dB/km
Atten @ 1550 nm 0.30 dB/km

Physical Properties

Diameter = 0.500"
Weight in air = 0.339 lb/ft
Weight in sea = 0.252 lb/ft
Cable Modulus = 23.9 Km

Mechanical Properties

Break Strength 19,800 lbf
Torque @ WL ≤ 24 in.-lbs
Rotation @ WL ≤ 1.2 deg/ft

Figure 15. Illustration of Simplex Design

degree-of-difficulty when compared to the options of using round copper wires. Further, since the technique of applying shaped segmented copper is a non-standard cabling process, it would likely involve more development.

Simplex conducted a very aggressive Phase II cable development program. Although they were not able to deliver a 15 km continuous length cable on the first try, they came fairly close to this achievement. They did deliver a 4.7 km continuous length in a timely fashion--late January 1990; such that they were included in the Phase II test program on schedule. Also, they proposed certain design modifications to their 4.7 km cable, and fabricated a 10.4 km continuous length of cable, which completed their contract requirements. The cable was delivered in mid-May 1990.

Preliminary testing results indicate that **Simplex built the strongest Phase II ADWT cable (18,000 lbs min BS)**, such that they easily qualified their cable for the 9,000 lbf working load requirement. In fact, it appears that **the Simplex cable could be rated for an 11,000 lbf working load requirement** if needed.

From the optical performance standpoint, Simplex met the requirement for $\leq$ 0.4 dB/km at 1310 nm. Although they also met the $\leq$ 0.3 dB/km loss at 1550 nm--they just barely met this value by showing a 0.3 dB/km loss at 1550 nm in the 4.7 km cable. The reason for this excessive loss as compared to the typical 0.2 to 0.22 dB/km loss values demonstrated by the other vendors at 1550 nm, is believed to be the result of a minor manufacturing process error. During fabrication of the recently delivered 10 km cable length, Simplex increased the tension on the steel tubed fiber element during fabrication of the electro-optic strand, and this resulted in achieving the 0.21 dB/km loss value at 1550 nm.

3.5.1 Electro-Optic Strand Configuration. Simplex used the shaped, segmented copper design as shown in NOSC's Rev. B spec for construction of the electro-optic strand. As stated in the previous paragraph, they initially had trouble with this process, which also caused the original severing of the continuous 15+ km length of steel tubed fiber component as received from their subcontractor, Laser ArmorTech. The process used, however, appears to have a great potential for the future, in that it is a relatively high-speed process that combines both the electro-optic stranding and the insulation extrusion in one tandem process. This process will now be described. Some of the information is taken Simplex's "Technical Proposal to Western Instruments Corporation" dated 7 July, 1989; supplementary information is taken from the various visits to Simplex Wire & Cable during the fabrication.

As can be seen from the cable cross-sectional drawing, the electrical conductor consists of eight shaped copper segments laid circumferentially about the central steel tube which contains the optical fiber. These pre-shaped segments are designed to fit closely around the 0.032" OD central steel tube. The total cross-sectional area of these electrolytic tough pitch (ETP) copper sectors is 23,050 circular mils to provide a maximum DC resistance

of 1.5 ohm/km or less, at 20° C. The finished assembled conductor has a hardness in the 3/4 to full hard range. The conductors are applied with a 0° lay-angle in a continuous operation that includes tandem extrusion of the insulation over the copper strand as assembled about the steel tube. A very small quantity of conductor blocking compound (0.5 lbs/ft) was applied over the central steel tube. The eight pre-cleaned and pre-shaped copper segments were fed into the closing die with an initial tension of about 5 lbs. The segments were paid off of stationary bobbins through a series of guides and guide rollers towards the closing die. The actual line used at Simplex is referred to as "Extrusion Line 2-6."

The central steel tube was maintained at about 1.2 lbs back-tension originally, while being fed from a stationary bobbin and through a blocking applicator to control rate of compound application. As the segments closed down onto the steel tube the very light coating of liquid compound (GE Silastic or equivalent) was displaced into the very tiny interstices of the segments at the steel tube interface. The closed conductors passed through a precision sizing die to produce a finished diameter of 0.160 ± 0.003". A linear low-density polyethylene was simultaneously extruded around the composite copper and steel strand.

After passing through the copper stranding closing die, the 0.160" OD conductor was fed directly into the extrusion head to receive a nominal 0.062" wall of linear low-density polyethylene to a nominal 0.284 ±0.004" cold diameter. Minimum allowable wall thickness at any point was stated by Simplex to be 0.050" at any point.

Simplex stated that the adhesion of the conductor to the dielectric was tested on a 3 inch effective length to meet a target of 60 lb/inch or more at a pull rate of 1 inch/minute. Based on these results, Simplex did NOT adopt the alternate approach of extruding Dow Primacor 3330 adhesive polymer directly over the copper strand.

The use of the linear-LDPE resulted in slightly more pronounced impressions of the surrounding first layer of steel wire armoring into the outer surface of the insulation. However, it was agreed after some debate that the extent of the impressions was not so severe as to present a problem. It is noteworthy, however, that linear-LDPE has a lower softening and melting point than MDPE; consequently, the effect could be significantly more pronounced if the cable were handled or deployed from aboard ship in hot weather.

Although Simplex originally planned to use Union Carbide Co.'s DFDA-1184 Medium Density Polyethylene (MDPE), they proposed changing to linear low-density prior to actual fabrication. The reason given for this change was that linear low-density is more readily available. In addition, "linear-low" has gained more attention in the past few years as a low density compound having mechanical properties similar to MDPE.

A month earlier, when NOSC attempted to obtain pricing of DFDA-1184 MDPE from Union Carbide for the Navy's cost study they were informed by company representatives that they could not quote this compound to the Navy without permission from AT&T, who had funded its

development. This is the same MDPE used by Simplex in the manufacture of both commercial SL and FDS DWT cable.

Extrusion Line 2-6 is located in the Armored Cable Department at Simplex. It is accessible from reel stands, stationary cribs, pan stations, and the tank building. The extruder is a 4-1/2 inch, 24:1 unit capable of 600 lbs/hr depending upon the type of plastic. The line is equipped with access to silos with 40 klbs of polyethylene storage capacity. The on-line hopper/drier system is capable of preheating and drying up to 3 klbs of PE. The extruder and cooling trough control systems are capable of handling the most critical of materials. Gauging and instrumentation is available to control and continuously monitor diameter, speed, footage, wall thickness, and jacket integrity. The take-up capability also includes reel, pan, tank, and rail car. Take-up for the 15 km length was done by reel.

The stainless steel tubed fiber optic is fed from a controlled payout reel through a bell-mouth and airwipe. A metered blocking compound applicator deposits a prescribed amount of blocking compound around the tube, which is suspended horizontally until reaching the closing die. The copper sectors, mounted on controlled brake bobbins on a non-rotating armor cage are guided through special roller guides that maintain their proper orientation and prevent twisting. The segments converge over the stainless steel tube at the closing die, which is precisely sized to provide a slight amount of compaction. Next, the formed electro-optic center passes to the extrusion head of the Killion 2-1/2 inch extruder, which is fed with linear-LDPE through the closed delivery system. Insulation is pressure extruded. A two-plane laser gauge provides continuous hot diameter information to the line operator. The cable passes through a series of three (3) cooling troughs with graduated temperature profile. Next, an air-wipe removes excess water as the cooled core exits the last trough and the cable passes through a calibrated counter, cold diameter two-plane laser gauge, eccentricity monitor, and 3000 Hz sparker to the set-speed belt type caterpillar which controls line speed. Next, the insulated conductor passes through a dancer to a take-up stand. The process limits core tension to no more than 100 lbs.

The attempted 15 km run, which occurred in October 1989, resulted in an unexpected event after about 5 km. Apparently, the 1.2 lbs tension placed on the steel-tubed fiber pay-off was insufficient with respect to the tension on the copper segments and the tension on the assembled, extruded core as it passed through the extrusion line. The steel tube apparently experienced a gradual build-up in axial compression within the extruded copper strand structure, because all at once at the 5 km point, an excess length of steel tube was developed between the exit of the copper closing die and the entrance into the rear head of the extruder. This could be explained by having more strain induced in the copper segments during fabrication than in the steel tube. Gradually, as the polyethylene insulated strand passed through the water troughs for cooling, it would tend to "shrink-back" or contract axially to

allow the copper strand to contract towards its original unstrained length. The radial pressure could tend to "drag" the steel tube with it, consequently, placing it into axial compression. By accumulating gradually an excess force, it could finally exceed the radial forces of the guide rollers tending to hold the assembled strand together. The tube finally burst through the assembled strands and caught in the pre-heat apparatus to destroy the steel tube's continuity. Although this caused a failure in the first run, the problem was easily corrected for the second run, because as soon as Simplex increased the tensions on the steel tube during pay-off, it was possible to strain match the steel tube with the copper. In this way, when the copper returned to its original unstrained length the steel tube followed. Simplex easily made a 10+ km length on the second attempt.

3.5.2 **Torque Balanced Double Steel Armor.** The armor package on Simplex's first ~5 km delivered cable contained the construction as proposed on their original cross-sectional drawing, Figure 15. The design had 21 steel wires of 0.046" OD, special, galvanized improved (SGIPS) plow steel wires applied preformed around the 0.284" OD insulated core. They were supposed to be applied at 10° right-hand (RH) lay (5.88" RH lay-length) to provide 94.6% coverage. A second layer of 36 preformed 0.032" SGIPS wires was applied at 7.27" LH lay-length (-10° with 91.3% coverage). In fact the actual lay-lengths were slightly greater than the planned values (as can be seen in Tables 3 and 4 to be discussed later). Simplex experienced some difficulty obtaining suitable preform in the relatively small outer lay wires at such a shallow helix angle (10°). This led to some instability in the outer layer, which caused difficulties during the outer jacketing extrusion as described in the next section below.

When making the additional 10 km deliverable that was completed in early May 1990, Simplex chose to modify the steel armor design slightly to improve its preform. The lay-angles were therefore increased from nominally 10° to about 13° in both layers. Also, the first layer used 20 steel wires of 0.048" SGIPS, while the second layer continued to used 36 steel wires at 0.032" OD each. The increased lay-angle decreased the effective radius of curvature of the wires within the helical path from 6.77" to 4.07", which explains why the wires were more easily given good preform or "permanent cast" during the second fabrication run.

3.5.3 **Manufacturing Issues.** As stated above, there were two manufacturing issues associated with the Simplex cable fabrication. First, the steel tube fiber component had to be held under greater tension during the copper stranding/insulation extrusion process to prevent axial compression of the tube from becoming a problem. Also, it was noted that the first cable delivered, the ~5 km length, demonstrated slightly "high" optical attenuation at the longer wavelength--1.55 microns--which is indicative of the tube's being compressed, which placed additional axial compression into the optical fiber within the steel tube. Ordinarily, the fiber within the tube will already contain a slight excess length of optical fiber after completion of the steel tube welding process.

This excess length causes the fiber to take the shape of a helix within the tube. When the tube is compressed, the fiber may experience slight axial buckling, and scatter light out of the waveguide. Since the optical attenuation at 1.55 micron was $\leq$ 0.3 dB/km the cable met the Navy requirement. However, other steel tubed fiber cables from other vendors demonstrated $\leq$ 0.22 dB/km optical attenuation--suggesting something slightly out of balance in the Simplex cable. Under hydrostatic pressure testing, which causes a slight axial elongation of the cable due to Poisson's ratio when the cable is radially compressed, the optical attenuation of the fiber dropped to 0.22 dB/km. This substantiated the fact that the steel tube indeed was in axial compression. When the steel tube was placed under increased tension during the manufacture of the remaining 10 km cable, the resulting optical attenuation at 1550 nm dropped to 0.22 dB/km.

The second manufacturing issue concerned the application of relatively small wires at a shallow 10° helix angle in the second armor layer. This occurred during the first fabrication attempt, thus the slightly unstable armor wires made it difficult to <u>pressure</u> extrude the outer HDPE cable jacket. The slightly loose steel wires tended to produce a "milking back" of the steel wires from the extrusion die towards the cable pay-off area. These "high wires" then tended to reduce the thickness of insulation over the apex of these wires. In fact, Simplex reportedly had several regions were the steel wires either "broke through" the HDPE jacket or created a sufficiently thin jacket thereover to cause Simplex to attempt "jacket repairs" at several places along the original 15 km of cable. Unfortunately, apparently because Simplex had switched from the MDPE insulation to the linear-LDPE, the linear-LDPE softened and melted at a lower temperature than the MDPE, resulting in the center copper conductor's shorting to the steel armor wires at several places. Consequently, Simplex was able to deliver only the 4.7 km piece that demonstrated electrical continuity. The 10 km re-make cable used increased lay-angle in the outer steel wire layer, which enabled a better steel wire preform and stability.

To improve extrudability of the outer HDPE jacket even further, Simplex proposed that the outer jacket be changed from a <u>pressure</u> extruded jacket to a tubular extrusion. Simplex argued that the tubed jacket would provide nearly the same degree of mechanical coupling as the pressure extruded jacket--due to the fact that they would use an amorphous polypropylene void-fill compound within the outer layer steel strands. Simplex believed that this highly viscous blocking compound would provide so much "shear transfer" between the cable core and the outer cable jacket, that it would not be necessary to use <u>pressure</u> extrusion in order to obtain integral mechanical bonding. In fact the second cable at 10 km, as delivered in mid-May 1990, did contain the tubed outer HDPE jacket. However, preliminary evaluations suggest that the tubed jacket is NOT integrally fused to the cable structure within this jacket.

The lack of mechanical bonding of the HDPE jacket to the armored cable core can be appreciated most easily as follows. When a small sample, say several feet in length, of the cable is cut, the outer

jacket will automatically contract axially to expose some length of the "bare" steel armored core. This shrink-back phenomenon occurs because of the residual stresses captured within the HDPE plastic during tubular extrusion. If the jacket were truly fused to the core, it would not be possible for the plastic jacket to shrink back in this way. This phenomenon is very pronounced in the Simplex cable. **The only reason for the tubular extrusion is to reduce the risk during outer jacketing. However, as is well known within the undersea cable community, it is either necessary to pressure extrude the outer jacket or to "glue" the outer jacket to the underlying structure with something like Dow Primacore 3330 (ethylene acetate copolymer).** The former method is preferred for the alternate Phase II design--and the latter is mandatory for the AT&T/Simplex CSM cable.

3.5.4 Ability to Support Volume Production. Simplex states that they could support a reduced rate of volume production using existing equipment. Although they were not specific about the exact rate, it appears from their methods used in Phase II that they could support over 100 km/month using the same equipment--possibly as much as 125 km/mo. In order to transition to a true production mode that would support 100-150 Nmi/mo, however, Simplex stated that they would require about 8-10 months to design, procure, install, and prove in the new equipment. The capital costs of this equipment were estimated at:

PRIMARY INSULATION LINE	\$100-150 K
ARMORING LINE	\$950-1050
JACKETING LINE	\$ 75-100 K
TOTAL:	~\$1.2-1.3 M

This is about an order of magnitude less capitalization costs than Simplex estimated for installing one line to make CSM type cable.

Consequently, Simplex estimated, that the **selling cost for their alternate OSM/steel tubed cable would be less than half the expected selling cost of AT&T's CSM cable** (based upon prices provided to AT&T by Simplex in June 1989). This estimated selling cost is especially interesting since Simplex has so much experience in volume production of undersea fiber optic cable. Also, Simplex is the only cable vendor involved in this effort who made a thorough investigation of the cost differences for the CSM and OSM cable design approaches.

4.0 DESIGN ANALYSIS, PERFORMANCE AND MANUFACTURING SUMMARY

4.1 SUMMARY OF DESIGN AND AS-MANUFACTURING DIMENSIONS

The following tables summarize the dimensions of the various Alternate cables which have been built. The "as-built" dimensions were used to perform computerized analyses of the cable constructions in order to determine the optimum configurations for future design iterations and manufacturing of the alternate cable.

Table 2 displays the dimensions proposed by the three vendors who were awarded contracts in Phase I. These dimensions were submitted with the proposals and represent pre-fabrication estimates.

In Table 3, the as-built dimensions of the Phase I Alternate cables can be found. Tension Member Technology (TMT) of Huntington Beach, CA performed the measurements on samples of the cables sent to them by NOSC. TMT conducted the mechanical testing of all the Phase I and Phase II cables.

Table 4 contains the proposed dimensions of the Phase II cables. The dimensions were taken from the drawings included in the proposal packages. The STC cable is based on the subsequent revision to the design, since the original included only one optical fiber and hence a smaller steel tube.

Table 5 shows the as-built dimensions of the Phase II cables as delivered to NOSC. The measurements were taken by TMT.

Comparing the dimensional goals of the manufacturers to the actual dimensions of the cable samples demonstrates that the vendors followed their proposed designs and did not find it necessary to radically alter the dimensions to ease manufacturing. The dimensional tolerances demonstrated in both Phase I and Phase II are representative of the relative ease of the fabrication process.

Table 2. Phase I Dimension as Proposed by Manufacturers

PHASE I ALTERNATE FDS CABLE
DIMENSIONS AS PROPOSED BY MANUFACTURERS - PRE-FABRICATION DESIGN

	Consolidated	STC England	Rochester
Steel Tube	0.032"	0.032"	---
Buffer - HYTREL	---	---	0.065"
Copper Strands	7+13+19x0.025" Three Layers	6x0.059"x0.064" Compacted	6x0.076"x0.055" Keystone elements
Outside Diameter	0.185"	0.162"	0.170"
Lay Length	?	3.638" Right	Parallel Lay
Strand Shield	0.200"	0.185"	---
MDPE Dielectric	0.280"	0.282"	0.300"
First Armor Layer	28x0.032"	28x0.031"	36x0.026"
Outside Diameter	0.344"	0.344"	0.346"
Lay Length	?	3.075" Right	?
Second Armor Layer	46x0.023"	46x0.023"	36x0.031"
Outside Diameter	0.390"	0.392"	0.408
Lay Length	?	3.55" Left	?
HDPE Jacket	0.468"	0.472"	.498"

Table 3. Phase I Dimensions as Measured by Testing

PHASE I ALTERNATE FDS CABLE
DIMENSIONS AS MEASURED BY TENSION MEMBER TECHNOLOGY

	Consolidated	STC England	Rochester
Steel Tube	0.032"	0.032"	---
Buffer - HYTREL	---	---	0.060"
Copper Strands	7+13+19x0.025" Three Layers	6x0.059"x0.064" Compacted	6x0.076"x0.055" Keystone elements
Outside Diameter	0.082",0.129",0.179"	0.162"	0.175"
Lay Length	2.238" Left	3.638" Right	Parallel Lay
Strand Shield	0.189"	0.185"	---
MDPE Dielectric	0.303"	0.282"	0.298"
First Armor Layer	30x0.031"	28x0.031"	30x0.031"
Outside Diameter	0.365"	0.344"	0.361"
Lay Length	3.167" Right	3.075" Right	2.616" Right
Second Armor Layer	24x0.031"	46x0.023"	48x0.023"
Outside Diameter	0.437"	0.392"	0.409
Lay Length	3.413" Left	3.55" Left	3.560" Left
HDPE Jacket	0.487"	0.472"	.500"

Table 4. Phase II Dimensions as Proposed by Manufacturers

PHASE II ALTERNATE FDS CABLE
DIMENSIONS AS PROPOSED BY MANUFACTURERS

	Consolidated	Simplex Version 1	Simplex Version 2	STC
Steel Tube/Fibers	0.033"	0.032"	0.032"	0.046"
Copper Strands	7x0.0253", 7x0.052" Two Layers	8x0.058"x0.064" Keystone elements	8x0.058"x0.064" Keystone elements	6x0.062" x0.058" Compacted
Outside Diameter	0.170"	0.160"	0.161"	0.160"
Lay Length	2.75" Left	Parallel Lay	Parallel Lay	3.59" Right
Strand Shield	0.190"	---	---	---
MDPE Dielectric	0.290"	0.284"	0.284"	0.284"
First Armor Layer	26x0.038"	21x0.046"	20X0.048"	24x0.040"
Outside Diameter	0.366"	0.376"	0.380"	0.360"
Lay Length	5.365" Left	5.88" Right	4.52" Right	3.43" Right
Second Armor Layer	49x0.024"	36x0.032"	36x0.032"	40x0.028"
Outside Diameter	0.414"	0.440"	0.444"	0.416"
Lay Length	5.560" Right	7.27" Left	5.61" Left	4.00" Left
HDPE Jacket	0.500"	0.500"	0.525"	0.525"

Table 5. Phase II Dimensions as Measured by Testing

PHASE II ALTERNATE FDS CABLE
DIMENSIONS AS MEASURED BY TENSION MEMBER TECHNOLOGY

	Consolidated	Simplex Version 1	Simplex Version 2	STC
Steel Tube/Fibers	0.033"	0.033"	0.033"	0.046"
Copper Strands	7x0.025", 7x0.050" Two Layers	8x0.058"x0.064" Keystone elements	8x0.058"x0.064" Keystone elements	6x0.062" x0.058" Compacted
Outside Diameter	0.080", 0.171"	0.161"	0.161"	0.165"
Lay Length	2.703" Left	Parallel Lay	Parallel Lay	3.608" Left
Strand Shield	0.189"	----	----	----
MDPE Dielectric	0.291"	0.285"	0.285"	0.282"
First Armor Layer	26x0.0386"	21x0.046"	20x0.0480"	24x0.040"
Outside Diameter	0.366"	0.375"	0.376"	0.359"
Lay Length	5.529" Left	5.942" Right	4.528" Right	3.472" Right
Second Armor Layer	49x0.0242"	36x0.032"	36x0.0326"	40x0.027"
Outside Diameter	0.414"	0.439"	0.441"	0.417"
Lay Length	5.557" Right	7.450" Left	5.656" Left	3.988" Left
HDPE Jacket	0.508"	0.503"	0.530"	0.528"

4.2 PREDICTED CABLE PERFORMANCE VS. ACTUAL PERFORMANCE

4.2.1 Phase I Analysis. Table 6 lists the torque, rotation, elongation and ideal break strength of the three Phase I designs. The actual test values measured by TMT have been compared to computer generated predicted performance of the ADWT cables. These computer models were originally manipulated by TMT with the aide of NOSC in May 1989 and were duplicated for complementing the Phase II analysis. The results of the computer analysis reasonably match the actual mechanical testing data.

The STC and Consolidated Phase I cables were modelled employing a known core reduction, a reduction measured in testing. The "core" consists only of the medium density polyethylene annulus, which is known to compress 0.0012 inches during axial loading to the working load of 5,000 lbf. Given this known core reduction, the model computed the torque, rotation, elongation and break strength. The Rochester cable was modelled slightly differently, using an unknown reduction but known material parameters. From the material parameter inputs, the compression of the dielectric core was computed. The mechanical properties were computed from the material compression's relation to elongation and deformation. Both models generated numbers which reasonably matched the testing data.

4.2.2 Phase II Analysis. The Phase II comparisons, Table 7, are based on a model of a compressible dielectric core, "core" referring to the medium density polyethylene dielectric annulus between the copper stranding and the armor. No pressure external to the cable was assumed. While the model does not exactly match the tested data, the agreement is good, and indicates that designs that meet the performance specification according to the model would also meet the specifications in actual testing. The greater discrepancies seen in the Phase II analysis are not unexpected because of the simplicity of the model being used. The important result is that the correlation between the model and test data is good enough to warrant basing future design modifications on the design's performance in modelling.

The material parameters were generally taken to be average values for the materials. The Laser Armor Tech steel tube was modelled having an elastic modulus of 40 kpsi, an ultimate yield stress of 150 kpsi, and a yield stress of 120 kpsi. Extensive testing has been previously done on the steel tube and the product is consistent. The medium density polyethylene dielectric was modelled with a 3 kpsi ultimate stress and a 1.5 kpsi yield stress, which are average values for this type of plastic. The high density polyethylene was also modelled in the mid-range of typical values for these plastics: 5 kpsi ultimate stress and 3 kpsi yield stress.

Table 6. Phase I Performance - Predicted vs. Actual

PHASE I
STC SUBMARINE CABLE SYSTEMS

	Predicted	Actual
Torque @ 5,000 lbf	-6 in-lbf	-6 in-lbf
Rotation @ 5,000 lbf	-1.3 deg/ft	-1.2 deg/ft
Elongation @ 5,000 lbf	0.57%	0.58%
Break Strength	11,980 lbf (ideal)	11,700 lbf

PHASE I
CONSOLIDATED PRODUCTS CORPORATION

	Predicted	Actual
Torque @ 5,000 lbf	-18.4in-lbf	-17 in-lbf
Rotation @ 5,000 lbf	-3.1 deg/ft	-3.1 deg/ft
Elongation @ 5,000 lbf	0.596%	0.56%
Break Strength	11,850 lbf (ideal)	12,000 lbf

PHASE I
THE ROCHESTER CORPORATION

	Predicted	Actual
Torque @ 5,000 lbf	+6.6 in-lbf	+7 in-lbf
Rotation @ 5,000 lbf	+1.0 deg/ft	+1.3 deg/ft
Elongation @ 5,000 lbf	0.556%	0.52%
Break Strength	12,440 lbf (ideal)	12,550 lbf

Table 7. Phase II Performance - Predicted vs. Actual

PHASE II
STC SUBMARINE CABLE SYSTEMS (STC2-1)

	Predicted	Actual
Torque @ 8,000 lbf	-1.3 in-lbf	-2 in-lbf
Rotation @ 8,000 lbf	-0.2 deg/ft	-0.4 deg/ft
Elongation @ 8,000 lbf	0.625%	0.65%
Break Strength	15,230 lbf (ideal)	14,050 lbf

PHASE II
CONSOLIDATED PRODUCTS (CPC2-1)

	Predicted	Actual
Torque @ 9,000 lbf	-3.8 in-lbf	-4 in-lbf
Rotation @ 9,000 lbf	-1.1 deg/ft	-1.4 deg/ft
Elongation @ 9,000 lbf	0.634%	0.66%
Break Strength	16,840 lbf (ideal)	16,100 lbf

PHASE II
SIMPLEX VERSION 1 (SWC2-1)

	Predicted	Actual
Torque @ 9,000 lbf	+4.2 in-lbf	+3 in-lbf
Rotation @ 9,000 lbf	+1.2 deg/ft	+0.8 deg/ft
Elongation @ 9,000 lbf	0.487%	0.51%
Break Strength	19,540 lbf (ideal)	18,200 lbf

PHASE II
SIMPLEX VERSION 2 (SWC2-2)

	Predicted	Actual
Torque @ 9,000 lbf	+2.8 in-lbf	+3 in-lbf
Rotation @ 9,000 lbf	+0.8 deg/ft	+0.8 deg/ft
Elongation @ 9,000 lbf	0.508%	0.51%
Break Strength	19,710 lbf (ideal)	18,750 lbf

The tensile strengths of the armor wires and their cross sectional areas determine the differences between the cable designs. The copper stranding appears to contribute less in the modelling than in the actual handling of the cables, where the cables with parallel lay shaped segments (Rochester Phase I cable and Simplex Phase II cable) are noticeably stiffer than the cables with helical copper elements. This increased flexural rigidity likely reflects the fact that the shaped, segmented copper is in a hard, relatively brittle condition due to the cold working experienced during the shaping process. Typically, most round copper wire stranding is done with soft, bare copper in an annealed state.

The STC cable was assumed to use 285 kpsi tensile strength steel wires in both layers of the armor package, a tensile strength similar to that used in the Phase I designs. The Simplex cables were modelled with 290 kpsi steel in both layers, the dramatic increase in break strength being due apparently to a greater total cross-section of steel from the larger diameter wires used in the outer layer as compared to the other companies' designs. The Consolidated cable used the greatest tensile strength wires: 310 kpsi in the outer layer and 290 kpsi in the inner layer. However, as stated earlier, the size of the wires used in the outer layer was extremely small.

The primary conclusion that can be drawn from the computer modelling of the alternate cable's performance is that it closely matches the actual mechanical test results. This is extremely advantageous, since it is thus possible to confidently modify a given outer strength member cable design in order to improve its performance. Also, the main advantage of the outer strength member cable approach, i.e. the ability to readily adjust its design parameters in manufacturing, can readily be realized in practice. It is this flexibility in design, and the ability to confidently predict the impact on performance, that makes it possible to fabricate the steel tubed fiber cable in an outer strength member configuration on "conventional" cabling equipment. In effect, the cable design can be optimized for production on a given cable vendor's existing equipment. This means that nearly any cable company in the world having thermoplastic extruders and planetary cabling machines could built the OSM/steel tubed fiber cable!

4.3 PROPOSED CABLE DESIGN IMPROVEMENTS

The individual design aspects of the cables as produced by respective vendors have already been discussed. Below is a summary of the design options given in the "Seafloor EOM Cable Spec" and as pursued by various vendors:

(1) Three successful approaches to stranding of the copper about the steel tube containing the optical fiber have been identified. These include the eight shaped, segmented copper conductor as supplied by Simplex; the six semi-shaped round copper wires as stranded by STC-England; and the two-layer strand containing seven #22 AWG round bare copper wires in the first lay

and seven #16-1/2 AWG round bare copper wires in the second layer. All three of these approaches were successful both mechanically and electrically.

(2) For the best armor package, the wires must be given good preform. This was achieved by Simplex by increasing the second layer lay-angle from 10° to 13°, and by using only 36 wires of 0.032" OD each. STC obtained good preform by using a much steeper helix angle--about 17°--which was required in view of having a larger number (40) of smaller wires (0.027") in the second layer. Consolidated unexplainably used a very large number (49) of relatively smaller wires (0.024" OD ea.) in the second layer, and did NOT attempt to obtain preform. This was not catastrophic, but made cable handling during manufacturing and stripping for termination and repair more difficult.

(3) The outer HDPE jacket must be pressure extruded to achieve good mechanical shear transfer between the outer steel strength member and the jacket. Simplex used a <u>tubular</u> extrusion during fabrication of their last delivered 10 km piece of cable, and the jacket exhibited noticeable contractive creep on sample lengths. This proved that the jacket is NOT tightly bonded to the armored core. (It is possible that a tubular extruded jacket could be "glued" to the armored core by means of a true adhesive--i.e., Dow Primacor 3330--which is used in CSM cable fabrication of the MDPE dielectric over the central copper tube conductor, and to glue the outer jacket to the phosphor bronze tube shielding).

Finally, it is worth noting the possibility of using a "spaced" outer layer of steel wires as used in Consolidated Products Corp's Phase I cable. In the latter case good preform was obtained, and the jacket was extremely well integrated about the steel. An added variation on this theme would be the use of a HDPE plastic coating on the individual wires used in the second layer, in order to hold uniform spacing. This approach also brings up the possibility, as in CPC's Phase I design, that only 24 or fewer wires are needed in the second layer. (Many of the designs had 24 or fewer wires in the first layer). Armor designs with fewer than 24 wires in both layers can be fabricated on high-speed tubular armoring lines, which could possibly increase the production rate and yield, and reduce the selling cost.

4.4 SUMMARY OF ALTERNATE CABLE MANUFACTURABILITY

The alternate FDS cable, consisting of an outer strength member cable containing a central steel tube encased optical fiber element, can be readily manufactured on existing cabling machinery by at least four cable vendors. Three cable vendors demonstrated long length manufacturability in Phase II:

(1) Consolidated Products Corp (15 km);
(2) STC-England (10+ km, 8 km deliverable with 3 fibers);
(3) Simplex W&C (5 km, 10 km deliverables).

Also, a fourth cable vendor produced 33 km for another Navy Program:

(4) Vector Cable Co. (4 x 8 km ea. for John Schuster, OPNAV).

Finally, a fifth company--The Rochester Corp., produced several kilometers of steel tubed fiber cable with an outer strength member for AT&T in developing the ICC (Inter-connect Cable) for FDS. AT&T chose to use a version that did NOT contain the steel tubed fiber, but rather a plastic buffered fiber in the center of the cable. However, it is evident that TRC also has the ability to make the outer strength member/steel tubed fiber cable.

It is important to realize that Rochester's preferred approach to the OSM cable, which utilizes a Hytrel/Nylon buffer over the acrylate fiber (instead of the small-diameter steel tube), has <u>not</u> been able to meet both design and manufacturability requirements simultaneously. TRC's Phase I replacement cable was successfully manufactured in a <u>short</u> length (1 km) by using <u>standard</u> AT&T depressed-clad fiber. Their original Phase I cable employing AT&T <u>hermetic</u> fiber suffered multiple fiber breaks within a 1 km run. The <u>brittleness</u> of hermetic fiber may not be compatible with TRC's manufacturing process which closes shaped copper segments over the Hytrel/Nylon coated fiber. The use of the Hytrel/Nylon coating over <u>standard</u> fiber (without the use of the small-diameter steel tube) is unacceptable for extended (25 yrs) undersea application, since there exists no hermetic barrier within the cable.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions from the Alternate FDS cable development are rather simple, but they have profound implications.

(1) The outer strength member cable containing the small-diameter steel tube encased optical fiber element on the cable axis is a viable design approach for long-haul undersea applications.

(2) The OSM cable with steel tubed fiber optic element can be produced in long lengths ($\geq$ 15 km) by at least four vendors using existing, standard equipment. Many other cable vendors can likely make this cable, since conventional extruders and planetary cablers, the main equipment needed, are available in most cable plants throughout the world.

(3) The four vendors who have proved long length manufacturability indicated various time periods required to transition into full production: i.e. from 4 to 8 months. This is less than half the time required to facilitize for CSM cable production.

(4) The capitalization cost required to obtain full production varied from zero cost to the Navy up to $1.2 million maximum (Simplex). In other words, the capitalization cost is about an order of magnitude less than that required to obtain the capability to manufacture the CSM cable approach.

(5) The OSM cable strength can be varied easily between 12,000 lbs and 18,000 lbs. The rated cable working load can be designed at any value between 6,000 and 11,000 lbs. In other words, the strength of the OSM cable (Phase II) is typically double that of the CSM cable, and the working load is 50 to 100% greater.

(6) The OSM cable demonstrated consistently lower optical fiber attenuation values than previously produced CSM cables (we do NOT know the results of FY90 CSM fabrication/testing; in any event, the CSM cable is neither designed, specified, nor tested for the longer 1.55 micron wavelength transmission). None of the alternate OSM cables have exhibited discrete losses indicative of "optical anomalies."

(7) The OSM cable is a water-blocked cable. The CSM cable is a **non-waterblocked** cable that <u>requires hermetic fiber</u>.

(8) The OSM cable uses conventional, telcom grade fiber due to the hermetic enclosure provided by the steel tube. Hence, all of the materials and components used in the OSM cable are readily available "off the shelf." The CSM cable requires hermetic fiber, which is not yet available as an off-the-shelf item. (Both NOSC and NRL have been unable to purchase AT&T hermetic fiber even though they were ordered 6 and 12 months ago, respectively. Corning is still making changes to their "standard" hermetic fiber design.)

(9) The OSM cable provides an "armor" protection for the electro-optic functions in the cable. Hence, the OSM cable can be used in depths much more shallow than the $\geq$ 1,000 fathoms required for use of the 0.525"/CSM cable. This intrinsically reduces system cable cost, because not as much cable in a given system will require light armor, and/or medium or heavy armor. Additional armoring drives cable costs up dramatically. The survivability of outer steel strength member cable in the ocean has been proven for over one hundred years. Since 1972 alone, the Navy has used thousands of nautical miles of the SX-220 coax--a cable having the same generic configuration as the alternate FDS cable--in relatively shallow water range applications all over the world. The SX-220 coax has <u>less</u> steel than the alternate FDS cable (one layer of spaced steel armor). Some of these cables have been operational in shallow water (approximately 100 fathoms) for over 20 years.

(10) The OSM cable has proven easier to strip, terminate, and handle throughout the alternate FDS test program. This has been observed by both Navy laboratory technicians, and independent test personnel who conducted mechanical testing.

The Naval Ocean Systems Center recommends the adoption of the OSM cable design for FDS. In all technical aspects, whether because of intrinsic characteristics, actual test results, or by logical inference, this cable is superior to the CSM cable design. We believe it to be the lowest risk, most cost effective cable approach.

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This document covers the design and manufacturing of Alternate Deep Water Trunk Cable (ADWT), developed by the Naval Command, Control and Ocean Surveillance Center RDT&E Division, Advanced Applications Branch, for the Fixed Distributed Systems (FDS) Program Office–PMW 184, Naval Space and Warfare Systems Command. The purpose of this document is to provide information both on the specific design variations pursued by the various cable suppliers, and to provide insight on the manufacturability of cable built in accordance with the proposed designs at the respective vendors' facilities.

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21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE *(include Area Code)*	21c. OFFICE SYMBOL
K. Rogers	(619) 553–1521 email: krogers@nosc.mil	Code D714

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